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THE ORIGIN OF GUMBOTIL

GEORGE F. KAY AND J. NEWTON PEARCE
University of Iowa

The name gumbotil[1] was proposed recently for clays of distinctive characters which lie on glacial till and which are related closely to till. As originally defined, gumbotil is "a gray to dark colored, thoroughly leached, non-laminated, deoxidized clay, very sticky and breaking with starchlike fracture when wet, very hard and tenacious when dry, and which is chiefly the result of weathering of drift. The name is intended to suggest the nature of the material and its origin." In Iowa there is gumbotil on the Nebraskan, Kansan, and Illinoian drifts. It has not been developed on the Iowan drift nor on the Wisconsin drift.

SOME OF THE FORMER VIEWS REGARDING THE ORIGIN OF SUPERDRIFT CLAYS

Until recently these superdrift clays which are now called gumbotils had been found only on the Kansan and Illinoian drifts, in connection with which drifts the clays had been described under the name gumbo by several geologists.

Regarding the origin of this gumbo there have been various interpretations, some of which will be outlined briefly.

[1] George F. Kay, "Gumbotil, a New Term in Pleistocene Geology," *Science*, New Series, Vol. XLIV, November 3, 1916.

The gumbo of McGee.—Dr. W J McGee applied the name gumbo to the peculiar, tenacious clay which he found on his Lower Till,[1] and in referring to the habit of weathering of this till he states:[2]

> Where the clay is plastic and sand free and of the usual blue color, as in the superior peripheral portion generally, it commonly weathers whitish or ashen to a limited depth and forms a tenacious, intractable soil, drowning when wet and baking when dry. This phase is colloquially known as "gumbo," sometimes as "hardpan," and locally as "white clay," or (from its behavior below the plow) "push land."

The gumbo of Leverett.—Mr. Frank Leverett in his monograph "The Illinois Glacial Lobe" described the gumbo which he found associated with the Illinoian and Kansan drifts in southeastern Iowa.[3] He believed that the gumbo on the Illinoian drift was of the same age as that on the Kansan drift and favored the interpretation, although he was not satisfied fully with the view, that the gumbo is the result of aqueous deposition following submergence of the region.

The gumbo and loess-silt of Bain.—Dr. H. F. Bain, in his report on the geology of Decatur County, Iowa, states that blue to drab-colored gumbo which in places overlies the Kansan drift and is distinct from the drift belongs stratigraphically with the loess, and presents the view that the gumbo suggests a quiet-water deposit which has been compacted or puddled by water.[4] In earlier geological reports of counties in Iowa the same author refers to similar material. In his report on Keokuk County, Iowa, he refers to a stiff, yellow to blue-gray, plastic, non-calcareous clay which is on the Kansan drift and beneath the loess on the uplands, and states:[5] "It seems to be a deposit closely akin to the loess and

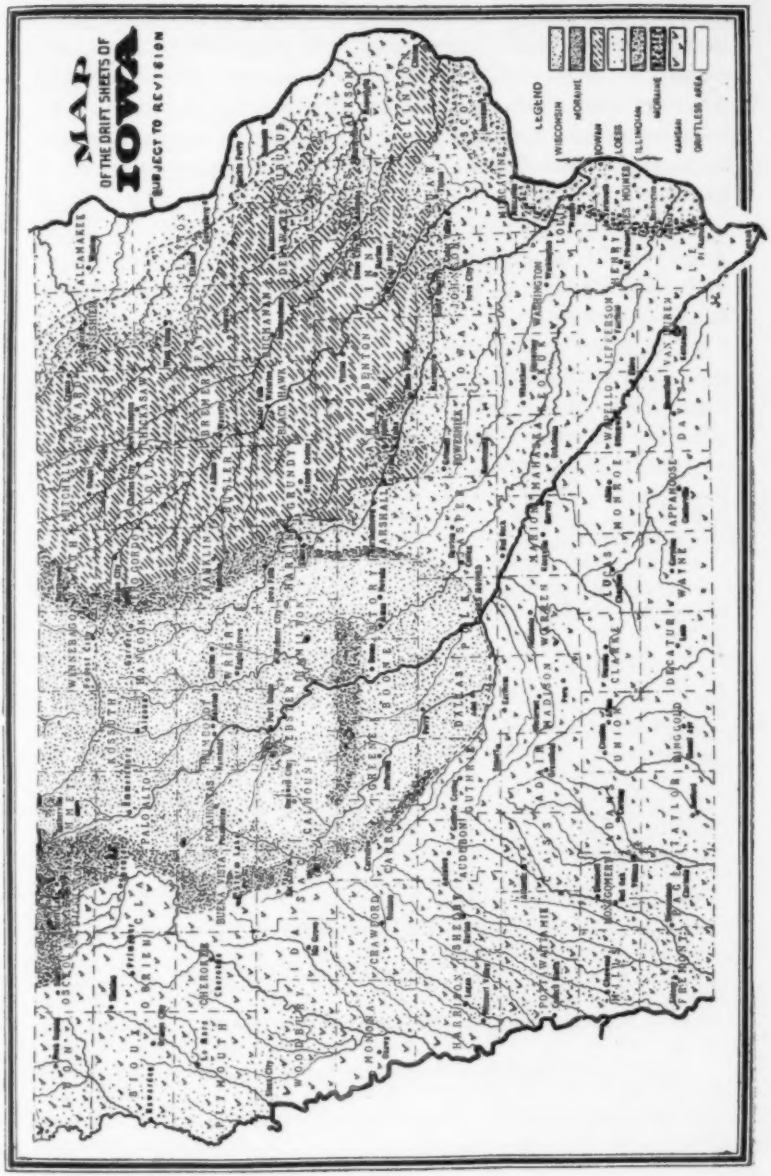
[1] Kansan drift of present classification.

[2] W J McGee, "The Pleistocene History of Northeastern Iowa," *U.S. Geol. Surv., Eleventh Ann. Rept.*, Part I (1891), p. 509.

[3] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv.*, Monograph XXXVIII (1899), pp. 28–33.

[4] H. F. Bain, "Geology of Decatur County, Iowa," *Iowa Geol. Surv.*, Vol. VIII (1897), p. 292.

[5] H. F. Bain, "Geology of Keokuk County, Iowa," *Iowa Geol. Surv.*, Vol. IV (1894), p. 302.


MAP
OF THE DRIFT SHEETS OF
IOWA
SUBJECT TO REVISION
LEGEND
WISCONSIN
MORAINE
IOWAN
LOESS
ILLINOIAN
MORAINE
KANSAN
DRIFTLESS AREA

probably genetically related to it. Very likely it is but a phase of that deposit though differing from it in its plasticity, color, and density." In his report on Appanoose County, Iowa, Dr. Bain describes a loess-silt[1] on Kansan drift which he considers to have been deposited later than the drift, and which in character and origin seems much like the white clays of Ohio Valley described by Leverett.[2]

In a geological report on Madison County, Iowa, Dr. H. F. Bain and Dr. J. L. Tilton refer to a dark-colored, impervious, unfossiliferous clay on Kansan drift as the lower of two phases of loess in the county.[3]

The gumbo of Udden.—Mr. J. A. Udden in a report on the geology of Pottawattamie County, Iowa, describes in considerable detail the gumbo or red clay associated with drift and makes the following statement regarding its origin:[4]

> It would be premature at the present time to express any opinion as to the origin of this deposit. Probably it is mostly an old loess, which has been clogged up by interstitial deposition of fine ferruginous material through the agency of the ground water. Perhaps it is in part a fluviatile deposit, made at a stage of semi-stagnant drainage, or possibly it is of varied origin, being in some places a surface wash, or a disintegration product derived from an underlying bowlder clay, and at other places a modified upland loess, or a river silt.

The Dallas formation of Tilton.—Dr. J. L. Tilton gave the name Dallas deposits to gumbo and related materials overlying Kansan drift in southern Iowa. He considered the deposits to have been formed during the closing stages of the Kansan glacial epoch.[5]

The gumbo of Arey.—In a report on the geology of Davis County, Iowa, Professor M. F. Arey states that the gumbo which lies on the Kansan drift is perhaps a water deposit.[6]

[1] H. F. Bain, "Geology of Appanoose County, Iowa," *Iowa Geol. Surv.*, Vol. V (1895), pp. 407–8.

[2] Frank Leverett, "On the Significance of the White Clays of the Ohio Region," *American Geologist*, Vol. X (1892), pp. 18–24.

[3] H. F. Bain and J. L. Tilton, "Geology of Madison County, Iowa," *Iowa Geol. Surv.*, Vol. VII (1896), p. 523.

[4] J. A. Udden, "Geology of Pottawattamie County, Iowa," *Iowa Geol. Surv.*, Vol. XI (1900), p. 258.

[5] J. L. Tilton, "A Pleistocene Section from Des Moines South to Allerton," *Iowa Acad. of Science*, Vol. XX (1913), pp. 218–20.

[6] M. F. Arey, "Geology of Davis County," *Iowa Geol. Surv.*, Vol. XX (1909), p. 511.

The Loveland of Shimek.—Professor B. Shimek proposed the name Loveland formation[1] for gumbo-like deposits related to Kansan drift in Harrison, Monona, and adjacent counties in southwestern Iowa. Detailed descriptions of the formation are given in his report on the geology of Harrison and Monona counties.[2] Here he refers to the fact that Mr. Udden described similar material in Pottawattamie County as gumbo or red clay. It should be pointed out that the Loveland of Shimek differs in some important respects from the Kansan gumbotil of southern Iowa. The gumbotil is found only on glacial till and has a definite topographic position. According to Professor Shimek the Loveland in places lies not on till but on gravels. Moreover, it is not confined to a particular stratigraphic plain; the term has been applied to material in the lower part of the bluffs along the Missouri River in some places as well as to material 180 feet higher than the bases of the bluffs. Shimek considers the Loveland formation to be a water deposit which was formed during the stage of melting of the Kansan ice, and which has the same relation in general to the Kansan drift as have the Buchanan gravels to Kansan drift. This interpretation may, however, be somewhat open to question, as recent studies indicate.

The super-Kansan gumbo of Alden and Leighton.—In a recent publication by Dr. W. C. Alden and Dr. M. M. Leighton there is a discussion of super-Kansan gumbo in Iowa. The authors do not commit themselves definitely with regard to its origin, but they present evidence which they consider favorable to the view advanced by Kay that the gumbo is the residuum of thorough weathering and long leaching of the upper part of the Kansan till.[3]

Sufficient evidence has been submitted to show clearly that the students of superdrift clays—the gumbotils and related materials—have been far from agreement regarding their origin. Some geologists have considered these clays to be mainly of fluvioglacial origin, others believe that they are aqueous, and still others have

[1] B. Shimek, "Aftonian Sands and Gravels in Western Iowa," *Bull., Geol. Soc. Amer.*, Vol. XX (1910), p. 405.

[2] B. Shimek, "Geology of Harrison and Monona Counties," *Iowa Geol. Surv.*, Vol. XX (1909), pp. 371–75.

[3] W. C. Alden and M. M. Leighton, "The Iowan Drift," *Iowa Geol. Surv.*, Vol. XXVI (1915), p. 91.

thought them to be related to loess. Until recently McGee was the only geologist who had stated definitely that the material which is now called gumbotil is the product of weathering of drift.

FIELD STUDIES OF GUMBOTILS AND RELATED MATERIALS

The conclusion which was presented by Kay in his paper in *Science* is:

> . . . . that the gumbotil is the result chiefly of the chemical weathering of drift was reached only after the field relations of gumbotil had been studied carefully, and detailed chemical analyses of Nebraskan gumbotil, Kansan gumbotil, Illinoian gumbotil, and the glacial tills underlying these gumbotils had been made.

The field relations of Kansan gumbotil to the underlying Kansan till have been already briefly described.[1] The Kansan gumbotil, there called super-Kansan gumbo, reaches a maximum thickness of more than twenty feet, and is limited to tabular divides and other remnants of a gumbotil plain which, before it was affected by erosion, was as extensive, apparently, as the original Kansan drift plain. This gumbotil occupies a definite topographic position, and where it is exposed in railroad cuts it is seen to lie horizontally in the cut and not to conform to the surface slopes which have been developed by erosion. The gumbotil is dense, sticky, and very slippery when wet, but is hard and very tenacious when dry. It is usually dull gray to drab in color; in places the gray color is mottled with brown and reddish tints. It is leached, but in many places it contains lime concretions. The dry surfaces of the exposures of gumbotil are distinctly checked by sun cracks. It contains only a few small, scattered pebbles, which consist predominantly of quartz and chert and subordinately of crystallines and quartzites. A striking feature of the quartz and chert pebbles is their remarkably smooth surfaces. The gumbotil grades downward into yellowish to chocolate-colored till, in many places with numerous pebbles, few if any of which are calcareous. This oxidized and non-calcareous till, in turn, merges into unleached

[1] George F. Kay, "Some Features of the Kansan Drift in Southern Iowa," *Bull., Geol. Soc. Amer.*, Vol. XXVII, pp. 115–17; reprinted in *Iowa Geol. Surv.*, Vol. XXV, pp. 612–15.

till, oxidized yellowish for several feet vertically, below which is the normal, unoxidized and unleached, dark grayish to bluish-black Kansan till. An impressive feature of the unleached, oxidized till is the presence of numerous concretions of calcium carbonate, the lime of the concretions having been dissolved in connection with the formation of the overlying gumbotil and leached till, carried downward and later precipitated.

Some sections showing the relations of Kansan gumbotil to underlying Kansan drift.—The following sections are given as typical of many sections that have been studied at widely separated places in the Kansan-drift areas of Iowa. They are intended to show the intimate field relations of the Kansan gumbotil to the underlying till.

Section in cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster Station, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous	2	
4. Loesslike clay, chocolate-colored, leached	1	6
3. Loesslike clay, light-colored, grayish; on dry surface looks like gumbotil; has chocolate-colored stains; sticky when wet; contains a few small siliceous pebbles; leached	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starch-like fracture when wet; leached	12	
1. Glacial till (Kansan), brown color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut	5	

Section in cut on the Chicago, Burlington & Quincy Railway at mile 372, one mile west of Murray Station, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color, with irregular lines of brown on dry surface; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy	15

	Feet
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions	11

Section in cut on Chicago, Milwaukee & St. Paul Railway no the divide about three miles west of Templeton, Carroll County, Iowa:

	Feet	Inches
4. Loess		
Buff-colored, leached	15	
Buff-colored, unleached	10	
3. Gumbotil (Kansan), gray to dark-drab to chocolate-colored, upper few feet reddish, a few small siliceous pebbles	20	6
2. Glacial till (Kansan), oxidized yellow to buff, leached, closely related to No. 3	7	
1. Glacial till (Kansan), oxidized, unleached; many calcareous concretions	8	

Section in cut on Santa Fe Railway east of New Boston, Lee County, Iowa:

	Feet
4. Loesslike clay, top 2 feet very light gray; below, yellow to light-brown on dry surface; when freshly cut into, more chocolate-colored; a joint clay; grades into No. 3	12
3. Gumbotil (Kansan), typical; gray on dry surface and has a checked appearance; when freshly cut into, has a more drab color; very sticky; contains some spots of brown; contains small siliceous pebbles; leached; grades into No. 2	12
2. Glacial till (Kansan), oxidized and leached; contains patches of gray similar to the gumbotil; many pebbles; grades into No. 1	5
1. Glacial till (Kansan), oxidized and unleached; contains many pebbles and small bowlders; many calcareous concretions; to the bottom of the cut, exposed	27

In all of these sections the zone of oxidized and leached till beneath the gumbotil is narrow. A study of thirty-five sections widely separated as to location shows that in eighteen of them the zone of oxidized and leached Kansan till beneath the Kansan gumbotil is 5 feet. In twelve of them it is 5 feet 6 inches; in the remaining sections the zone is somewhat more than 5 feet 6 inches or slightly less than 5 feet. The uniform thickness of the leached zone is impressive. The thickness of the oxidized, unleached zone of Kansan till is about 40 feet.

The distribution of Kansan gumbotil in Iowa.—The relations of Kansan gumbotil to the underlying Kansan till have been seen at scores of places in southern Iowa and at many places in other parts of the state. In fact the Kansan gumbotil has been studied in every county of three tiers of counties in southern Iowa as well as in many of the counties which are farther north.[1] Moreover, within the Iowan-drift area the Kansan gumbotil has been found beneath Iowan drift at numerous places.[2] It will be of interest to state that the Kansan gumbotil is now known at a sufficient number of places in Iowa to permit the restoration of the Kansan gumbotil plain, that is, the original plain surface of the weathered Kansan till, as it was in Iowa before any great erosion was accomplished.

Some sections showing the relations of Nebraskan gumbotil to underlying Nebraskan drift.—The field relations of the Nebraskan gumbotil to the underlying Nebraskan till are similar to the relations that have been described as existing between the Kansan gumbotil and the underlying Kansan till. The two tills, the Nebraskan and the Kansan, are much alike lithologically and both appear to have undergone similar changes under similar conditions. Below the Nebraskan gumbotil there is, as in the case of the Kansan gumbotil, a narrow zone of leached, oxidized till which grades downward into unleached, oxidized till with many concretions.

[1] George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 215–31.

[2] W. C. Alden and M. M. Leighton, "The Iowan Drift, a Review of the Evidences of the Iowan Stage of Glaciation," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 92–109.

A good section to show the field relations of the Nebraskan gumbotil to the underlying Nebraskan till is a railroad cut just east of a viaduct 1½ miles west of Manning, Carroll County, Iowa.[1] From the surface the cut shows loess, Kansan till, soil band, Nebraskan gumbotil, and Nebraskan till. The section is as follows:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions	7	
Unleached, lighter-colored on dry surface than the leached loess, and when damp is buff with gray streaks; contains shells and concretions	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray till with a few pebbles. It is gumbotil-like, but effervesces freely. It was probably picked up from the gumbotil zone below	5	
4. Soil band containing carbonaceous material		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper 6 feet is fine grained, gray, and is less sticky and gumbotil-like than the lower 7 feet, which is leached but has some calcareous concretions	13	
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp; many calcareous concretions, especially in upper 10 feet	17	

In Taylor County, Iowa, at a stream crossing just west of Conway Station on the Chicago, Burlington & Quincy Railway, is an exposure at which the following section was observed:

[1] George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), p. 225.

	Feet	Inches
4. Loesslike clay	1	
3. Gumbotil (Nebraskan), grayish to drab on dry surface; when damp, is grayish to brownish; a few siliceous pebbles; leached	11	
2. Glacial till (Nebraskan), oxidized and leached, many disintegrated bowlders	4	6
1. Glacial till (Nebraskan), oxidized, unleached, concretions, exposed	3	

Near this exposure Kansan till overlies the Nebraskan gumbotil.

Another interesting cut which shows Nebraskan gumbotil and underlying drift is along the wagon road west of Osceola, Clarke County, southwest corner of section 13, Ward Township, in front of a schoolhouse. The section is as follows:

	Feet	Inches
5. Loesslike clay, gray to light-yellow	8	
4. Glacial till (Kansan), oxidized, leached, ferretto zone on top	5	6
3. Glacial till (Kansan), oxidized, unleached, many concretions	8	
2. Gumbotil (Nebraskan), gray to drab-colored, sticky when wet, tough when dry, some calcareous concretions, a few siliceous pebbles; leached	10	
1. Glacial till (Nebraskan), oxidized, unleached; except in narrow upper zone, many calcareous concretions; bowlders and pebbles; above base of exposure	25	

Southeast of New Market and near the middle of the north boundary of section 5, Mason Township, Taylor County, Iowa, is a fine exposure of Nebraskan gumbotil with Kansan drift above it and Nebraskan drift below it. The section is as follows:

	Feet
4. Drift (Kansan), oxidized and unleached, many concretions	15
3. Gumbotil (Nebraskan), gray to drab-colored, leached, a few siliceous pebbles	8
2. Glacial till (Nebraskan), oxidized, leached	3
1. Glacial till (Nebraskan), oxidized, unleached, many calcareous concretions, exposed	22

The distribution of Nebraskan gumbotil in Iowa.—The Nebraskan gumbotil has been found in widely separated localities in Iowa. Among the many counties in which it has been studied are Decatur, Clarke, Warren, Madison, Union, Ringgold, Taylor, Adams, Adair, Cass, Montgomery, Page, Shelby, Crawford, Carroll, Tama, and Johnson counties. The topographic positions of the several outcrops indicate that the Nebraskan gumbotil was formed on an extensive plain with slight relief just as in the case of the formation of the Kansan gumbotil. The maximum thickness of Nebraskan gumbotil thus far studied is about thirteen feet. The zone of oxidation of the Nebraskan drift is rarely fully exposed; depths of oxidation of more than forty feet have been seen without the base of the zone of oxidation having been revealed.

Some sections showing the relations of Illinoian gumbotil to underlying Illinoian drift.—That the relations of the Illinoian gumbotil to the underlying Illinoian till are similar to the relations of Kansan and Nebraskan gumbotils to their respective tills may be shown by presenting two sections from many sections which are known to show similar relationships.

An exposure at the head of a ravine about one hundred yards north of the edge of the bluff north of Fort Madison, Lee County, gives a section as follows:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow in color	7	
3. Gumbotil (Illinoian), drab to chocolate to dark color, starchlike fracture, few pebbles, leached; grades into No. 2	4	6
2. Glacial till (Illinoian), oxidized, leached	6	
1. Glacial till (Illinoian), oxidized, unleached to base of gulch	15	

A splendid section to show, not only the Illinoian gumbotil and underlying Illinoian drift, but also the Kansan gumbotil and underlying Kansan drift, is a railroad cut on the Chicago, Milwaukee & St. Paul Railway between Fort Madison and Sawyer, in Lee County. The cut is in section 28, Washington Township, and shows the following materials:

	Feet	Inches
6. Gumbotil (Illinoian), gray to ashen-color on dry surface; on fresh surface, gray mottled with brown; small pebbles; leached; grades into No. 5	4	6
5. Glacial till (Illinoian), oxidized brownish, contains bowlders, leached	5	6
4. Glacial till (Illinoian), oxidized, unleached, has concretions, breaks into irregular shaped fragments	1	
3. Gumbotil (Kansan), drab to dark color, starchlike fracture, some calcareous concretions; few pebbles; leached; grades into No. 2	8	6
2. Glacial till (Kansan), oxidized, pebbles and bowlders, leached	5	
1. Glacial till (Kansan), oxidized, unleached, many concretions, breaks with irregular fracture, exposed	12	

The transition zone between gumbotil and the base of the oxidized leached drift.—Many interesting sections might be given to show disintegrated and decomposed bowlders in the transition zone between gumbotil and the base of underlying leached and oxidized till. For example, on the east-west wagon road in section 1, Otter Creek Township, Lucas County, Iowa, there is in the transition zone between the Kansan gumbotil and the base of the leached, oxidized Kansan till a granite bowlder with dimensions of 4×2 feet on the slope. It is so thoroughly weathered that its outlines are discerned only with difficulty. Again, in a cut through the upland $\frac{1}{4}$ mile north of Forbush on the interurban railway between Centerville and Moravia, Appanoose County, Iowa, there is in the transition zone between Kansan gumbotil and the base of the oxidized, leached Kansan till a completely disintegrated granite bowlder 5 feet long by 2 feet wide as exposed on the surface.

The pebble content of gumbotil and underlying drift.—The gumbotils and underlying tills were studied also with regard to their pebble content to ascertain whether or not additional evidence could be obtained to strengthen the view that the gumbotils are the result of changes in what was originally till.

The average pebble content of Kansan gumbotil gained from eight analyses of pebbles made in widely separated areas in Iowa is as follows:

	Percentage
Quartz	48.5
Chert, flint, etc.	31.8
Quartzite	6.8
Granite	7.8
Basalt and greenstone	2.9
Feldspar	1.0
Sandstone	0.5

It will be seen that more than 87 per cent of the pebbles are of siliceous material; the highest percentage of siliceous pebbles shown by any of the exposures of Kansan gumbotil subjected to study was 98 per cent, the lowest 75 per cent.

The average pebble content of the leached and oxidized Kansan till beneath the Kansan gumbotil is as follows:

	Percentage
Quartz	16.8
Chert, flint, etc.	16.5
Quartzite	8.0
Granite	20.3
Basalt and greenstone	24.5
Feldspar	1.0
Felsite	7.0
Sandstone	1.0
Shale	0.6
Quartz porphyry	0.5
Schist	2.3
Gneiss	0.3

The average content of siliceous pebbles is here only about 42 per cent, compared with 87 per cent in the Kansan gumbotil; the highest siliceous content was about 55 per cent, the lowest about 25 per cent.

A study of the pebble content of the unleached and oxidized Kansan till beneath the leached and oxidized Kansan till gave an average result as follows, seven analyses being used:

	Percentage
Quartz	6.4
Chert, flint, etc.	8.3
Quartzite	3.0

	Percentage
Limestone	40.0
Granite	11.0
Basalt and greenstone	27.0
Felsite	3.0
Sandstone	1.0
Slate	0.4
Schist	0.4

It is clearly seen that the content of siliceous pebbles of the unleached and oxidized Kansan till is considerably less than that of the leached and oxidized Kansan till, the average siliceous content of the former being less than 20 per cent.

It is of interest to note that the kinds of pebbles found in the different zones of material are much alike. Of course limestone is in the unleached zone only.

Similar results were obtained when the Nebraskan and Illinoian gumbotils and their respective underlying tills were studied. For instance, the average pebble content obtained from several analyses of Nebraskan gumbotil is as follows:

	Percentage
Quartz	36.75
Chert, flint, etc.	21.25
Quartzite	20.25
Granite	8.25
Basalt and greenstone	11.0
Feldspar	1.25
Felsite	0.50

The content of siliceous pebbles is here more than 78 per cent; none of the Nebraskan gumbotil examined gave less than 72 per cent, and the highest gave 88 per cent. The studies of leached and oxidized Nebraskan till gave about 38 per cent of siliceous pebbles, and the unleached and oxidized Nebraskan till gave about 15 per cent of siliceous pebbles.

Analyses of the pebbles of Illinoian gumbotil gave an average result as follows:

	Percentage
Quartz	43
Chert, flint, etc.	53
Quartzite	..
Granite	..
Basalt and greenstone	2
Sandstone	2

Analyses of pebbles of leached and oxidized Illinoian till beneath Illinoian gumbotil gave results as follows:

	Percentage
Quartz	28
Chert, flint, etc.	38
Quartzite	..
Granite	12
Basalt and greenstone	14
Feldspar	2
Felsite	5
Sandstone	1

These analyses show also that the percentage of siliceous pebbles in the gumbotil is much higher than that in the oxidized and leached till which underlies it.

The sizes of pebbles in gumbotil and underlying drift.—When pebbles from the gumbotils and underlying tills were being taken in the field the only purpose in mind was to ascertain the percentage content of the different constituents. Later, when these studies were being made in the laboratory, it became evident that the pebbles might also be used in estimating the relative sizes of the pebbles in the different horizons, and in determining the shapes of the pebbles.

One hundred pebbles collected from the Nebraskan gumbotil at one locality had dimensions as follows: largest pebble 2.4×1.4×1 cm., smallest pebble 2 mm., and average pebble 8×5 mm. The shapes of these pebbles were subangular to spheroidal. The unleached and oxidized Nebraskan drift beneath the Nebraskan gumbotil had pebbles with dimensions as follows: largest pebble 6.25×4.5×1.75 cm., smallest pebble 3×4 mm., and average pebble 1.75×1.5×1 cm. The pebbles were chiefly flat and subangular; some were slightly rounded.

The largest pebble in the Nebraskan gumbotil from another locality was 10×7×5 mm., the smallest 1.5×2 mm., and the average 3 mm.; the shapes were subangular to spheroidal. Here the underlying Nebraskan till had pebbles, the largest pebble of which was 5.5×3.5×3 cm., the smallest pebble 3×2 mm., and the average pebble 1.5×1×.75 cm. The shapes of the pebbles were subangular to more or less flat.

Similar studies made of pebbles taken from Kansan gumbotil and from underlying Kansan drift gave results as follows: largest pebble in gumbotil 3.2 cm., smallest pebble 3 mm., and average pebble 7 mm. In the underlying drift there are many pebbles 10–12 cm. in diameter, a few more than 3 cm. in diameter; the smallest pebble seen was 7 mm., and the average of one hundred pebbles collected was about 1.8 cm. The shapes of the pebbles were similar to corresponding horizons in the Nebraskan materials.

CHEMICAL STUDIES OF GUMBOTIL AND RELATED MATERIALS

In addition to a study of the field relations of Nebraskan gumbotil, Kansan gumbotil, and Illinoian gumbotil, the tills which underlie these gumbotils, and laboratory studies of the physical properties of these materials, there were made detailed chemical analyses of gumbotils and related materials. The specimens were taken from exposures which had been studied carefully in the field, and the materials selected were thought to represent satisfactorily the compositions of the zones from which they were taken. The analyses were made from 1-gm. samples of fine material which had been separated carefully from pebbles and concretions. Only the material which could be sifted through a "twenty-mesh" copper-gauze sieve was pulverized and subjected to chemical analysis. Accurate determinations were limited to the oxides of aluminum, silicon, iron, calcium, and magnesium, since deductions as to the nature of the chemical processes involved in the transformation of the drift can be made only upon the proportions of these less mobile constituents now present. The analyses were made in strict accord with the preferred methods and the recommendations prescribed by Hildebrand.[1]

Before referring in detail to the kinds of materials which were analyzed, the localities from which they were taken, and the results of the analyses, it seems well to discuss somewhat fully some of the geo-physico-chemical factors which need to be understood in order to interpret correctly whether or not a material such as gumbotil is the product of weathering of till. Chemical evidence will be presented to support the field evidence that the

[1] Hildebrand, "The Analysis of Silicate and Carbonate Rocks," *U.S. Geol. Surv., Bulletin 422.*

gumbotils and underlying oxidized and leached tills have been formed by chemical weathering and leaching of till which was originally unoxidized and unleached.

The abundant field evidence supporting this theory has been presented. Emphasis has been put upon the gradation of gumbotil into underlying till, the variations in the sizes of pebbles in the related zones, and the presence of remnants of thoroughly disintegrated and decomposed bowlders in the transition zone between gumbotil and oxidized and unleached till.

There have been profound changes involving chemical processes which operated during immense lengths of time, and which occurred long ages ago. These chemical processes are subject to a few definite, general physical laws of nature which are independent of time or place. The laws of stress and strain, of the degradation of energy, of hydrolysis, of mass-action, or of solution in general are as lasting as the universe itself.

The rôle of water in geochemical changes.—The dominant factor in all of these geo-physico-chemical changes is water, more especially the aerated water. When the rain falls upon the ground one part, the "run-off,"[1] flows over the surface and escapes by way of the natural drainage channels. It is this form which produces erosion. A second part, the "fly-off," immediately evaporates into the air, while the third part, the "cut-off," penetrating the soil by way of the soil interstices, flows downward under the influence of gravity. Of these the cut-off water is the only form which is directly effective in geochemical transformations. It moves through the soil and its substrata with comparative rapidity, reappearing elsewhere as seepage water or as springs.

The rain and surface waters contain dissolved oxygen, nitrogen, and carbon dioxide, each in proportion to its partial pressure in the atmosphere. The chemical and physical processes which are continually taking place below the surface involve the absorption and formation of carbon dioxide and the disappearance of oxygen and nitrogen. These gases impart to the soil an atmosphere, and their concentrations in the soil solution follow more or less slowly the barometric changes above the surface. The soil bacteria and

[1] This terminology was proposed by McGee.

other lower forms of life are likewise producing change and undergoing change continually.

According to Cameron[1] the water within the soil is in reality of two kinds, namely, "film" water and "free" water. When a relatively small quantity of water is added to an absolutely dry soil or powdered solid there is some shrinkage in the apparent volume of the solid; the water spreads over the surface in the form of a film. With further addition of water the apparent volume of the solid material increases until a maximum is reached. The optimum water content which gives the maximum volume is a definite, critical, physical, characteristic property for a given soil or solid. A further addition of water will not increase the thickness of the soil film but will produce free-water in the soil interstices.

These two kinds of water play an important rôle. The film-water is tenaciously held by the soil and subsoil particles. In dry seasons it is practically a saturated solution of the dissolved rock and soil materials. When the surface of the ground becomes flooded, as in wet seasons or during heavy rains, the downward-moving free-water extracts and carries away a part of the mineral content of the film solution. Obviously the proportions of water-soluble materials in soils containing moving free-water should be, and are, less than those in soils containing only film-water. This was conclusively shown by Hilgard.[2] In the humid regions there is a greater amount of rainfall, hence a greater amount of downward-moving free-water, consequently a greater amount of leaching.

Once the free-water is removed the saturation of the film-water repeats. In this film-water are the dissolved rock materials, the carbon dioxide, the oxygen, the nitrogen, the soluble humous material, and the soil bacteria. Between these are evolved all of the processes leading to the disintegration of the rock material and the formation of the soil and its substrata.

Chemical nature of glacial materials.—The rock materials transported by the glaciers consisted chiefly of silicates, quartz, some clays, and other previously weathered materials. The complex silicates are salts of a very weak acid—silicic acid, with various

[1] Cameron, *Jour. Phys. Chem.*, Vol. XIV (1910), p. 340.

[2] See Merrill's *Rock Weathering and Soils*, p. 368.

base-forming metals, like sodium, potassium, calcium, magnesium, iron, and aluminium. These silicates are only very slightly soluble in water. While the amount dissolved may be exceedingly slight, it is nevertheless sufficient for the purposes here involved, if the time allowed is sufficiently long. For a given rock material the solubility, and hence the speed, of the weathering process increases with increasing fineness of the particles. Hence the fineness of the glacier flour renders it peculiarly suitable for rapid chemical conversion.

Like all salts of weak acids with strong bases, these silicates when dissolved react chemically with water, that is, hydrolyze, to form the free more or less ionized bases—the soluble hydroxides of sodium and potassium, the less soluble hydroxides of calcium and magnesium, the relatively insoluble hydroxide of iron, and either the free un-ionized silicic acid or some simple silicates. These simpler silicates continue to hydrolyze, if the reaction products are removed. There results the liberation of still other bases and in the end still simpler silicates, possibly kaolin, or even silica as quartz or sand.

If the reaction products are not removed by leaching, the dissolved materials soon attain a state of solution equilibrium. Under these conditions the decomposition products of one rock material may react with those of another to form more or less complex silicates of a secondary origin. Let the saturated solution be removed and fresh water added, the various solution equilibria are disturbed and the solution processes begin again.

The solution and subsequent hydrolysis of rock material, and the chemical reactions involved.—In the soil solution thus formed the dissolved materials will at the proper concentrations react with the carbon dioxide of the soil atmosphere to form the soluble, easily hydrolyzable carbonates of sodium and potassium and the slightly soluble carbonates of calcium and magnesium. These slightly soluble carbonates crystallize out as calcareous concretions, so frequently found in the clay subsoils. In the presence of an excess of carbon dioxide these insoluble carbonates pass into the soluble acid-carbonates and are leached away by the downward-moving free-water to lower depths, where they are again deposited in the form of concretions.

Ferrous silicates upon hydrolysis give ferrous ions. These may react with other ions of the soil solution to form the slightly soluble ferrous hydroxide or carbonate, or, what is more probable still, they may be immediately oxidized to ferric ions by the dissolved oxygen and then precipitated as the insoluble hydrated ferric oxide or basic carbonate.

Some may raise the question as to the possibility of the oxidation of the iron below the surface and out of contact with the air above. It must not be forgotten that by virtue of diffusion not only oxygen but also other dissolved gases tend to go just as far as the water does. Except at points where organic matter is undergoing decay, it is very doubtful if more than minimal traces of secondary ferrous compounds exist within or beneath the soil.

Crystalloids and colloids.—The resulting so-called weathering products may be grouped into two great general classes, namely, crystalloids and colloids. Crystalloids include all of the soluble acids, bases, and salts. They are simple in structure, that is, they exist in the dissolved state either as molecules or as ions. They are characterized by a relatively high diffusion speed and by the power to pass, though more or less slowly, through colloidal membranes. Nor is the colloidal membrane lacking in the soil; the clay itself may be considered as such a membrane.

Generally speaking, the term colloid is applied to all glue-like, gelatinous, amorphous substances. Strictly speaking, colloids represent suspensions of matter in an extremely fine state of subdivision, the suspended particles having diameters varying from 1 μ to 100 $\mu\mu$. The properties of colloids are primarily surface properties. The extent of surface development, and hence the magnification of specific properties, such as solubility, adsorption power, etc., may be seen from the following illustration: A centimeter cube of any solid substance, say platinum, exposes a surface of 6 square centimeters. Let this cube be divided successively and decimally to the dimensions of colloid particles. The total surface then exposed by the platinum will vary between 60 and 6,000 square meters.

Some colloidal properties involved in this problem.—Since colloids play an important rôle in the formation of soil strata and since they

impart to these strata many of their most important properties, it will be necessary to mention in detail some of the more important colloid properties and phenomena.

Colloids are divided into two general classes, namely, suspensoids and emulsoids. Briefly stated, suspensoids are suspensions of solid particles, chiefly inorganic, in a fluid medium; emulsoids are suspensions of fluid or semi-fluid particles. The emulsoids found in the soil are chiefly of organic origin, resulting from the secretions of animals, the exudations of plant roots, the humus, and other products of decaying organic matter brought about through the assistance of bacteria and fungi.

Colloids are also classified as reversible and irreversible. Most of the suspension colloids when desiccated, sometimes when frozen, or when in the presence of electrolytes, coagulate into a solid or semi-solid water-insoluble precipitate. When this solid is placed in water it does not again pass into suspension. It is therefore said to be irreversible. To this class belong the hydrated ferric oxide, the gelatinous silicic acid, the gelatinous, hydrated aluminum silicates, the clays, kaolin, etc. In rare cases one may find aluminum hydroxide.[1]

Suspended colloid particles are either positively or negatively charged. Thus silicic acid, kaolin, and clay particles are negative; the basic hydrated ferric oxide is positive. These charged particles are precipitated by electrolytes, and it has been found that the precipitating power of the electrolyte is specifically a property of the ion bearing a charge opposite in sign to that of the particle. Further, the precipitating effect is greatest for those ions carrying the greatest number of charges.

Factors determining the stability of colloidal clay suspensions.—The effective properties of any colloid suspension depend upon its stability—its power to exist in the colloidally suspended state. The stability is also one factor in the slow transportation of the colloid particles through the soil capillaries. This stability depends not only upon the absence of precipitating ions but also upon the potential difference between the charged particles and the oppo-

[1] Cameron and Bell, "The Mineral Constituents of Soil Solution," *U.S. Dept. of Agric., Bull.* 30 (1905), p. 22.

sitely charged solvent. The stability is greatest when this potential difference is greatest; its instability, or its tendency to coagulate, is greatest when this difference approaches zero.

Electrolytic coagulation or precipitation is preceded by the electrical adsorption of ions by the oppositely charged colloid particles. The precipitate carries with it the adsorbed ion or its salt, which in its adsorbed state is more or less difficultly removed by washing. Thus certain salts like those of potassium and ammonium are specifically and tenaciously held by the soil and clays, while the more toxic, less firmly adsorbed sodium salts are leached away.

When present in traces the singly charged H^+ and OH^- ions not only do not coagulate colloidal material but may even increase the stability of similarly charged colloid particles. In the hydrolytic decomposition of the alkaline silicates free OH^- ions are formed. These tend to increase the negative potential, likewise the stability of the negative colloids. Thus in the alkaline-soil solutions silicic acid and the colloidal hydrated silicates are kept to a slight extent, at least, in a state of pseudo-solution. Under the influence of the free carbonic acid and of mineral acids formed by adsorption cleavage of the dissolved salts there may be, as in acid soils, a slight excess of H^+ ions. These stabilize those colloidal "sols" containing positively charged particles. Thus colloidal hydrated ferric oxide is, to a very slight extent at least, rendered capable of transportation by the downward-moving free-water. In the initial stages of the leaching of an original silicate material, where the solution is distinctly alkaline, only the soluble salts and the transportable negative colloidal silicic acid are removed by leaching. Not until the alkalinity has disappeared would it be possible for the positively charged colloidal ferric hydroxide to exist in suspension. Iron in the colloidal form would be, therefore, almost the last colloidal material to undergo leaching.

A soil or clay colloid when once coagulated may again pass into the soluble hydrosol condition. Numerous experiments have been made dealing with this particular problem. Van Bemmelen has found that when finely divided clay is washed upon a filter the loosely bound coagulating salts are washed away. Upon further

washing, the clay becomes still more finely divided and finally passes through the filter, giving a turbid non-settling suspension. On adding a small amount of an electrolyte the milk-white liquid coagulates and settles. Upon washing again another point is reached at which the particles become infinitely fine and pass through. So it is in clay soils: an excess of water percolating downward removes the excess of coagulating electrolyte from the leached clay. This permits first a swelling of the reversible colloidal material and finally, to a slight extent at least, the gradual re-formation of the colloidal "sol." The suspended particles are thus permitted to pass slowly downward, where they are again coagulated at some lower level.

The inorganic colloids of soils and clays exhibit a marked tendency to adsorb upon their surfaces the various organic emulsoids formed from plant and animal débris. The humus is full of these. The adsorbed emulsoidal material forms an oil-like film about the suspended particles and imparts to them its own reversibility and stability. Hence when a mixture of the emulsoid and suspensoid materials are evaporated to dryness and the dry material is again placed in water the whole mass again passes into colloidal suspension. Furthermore, if emulsoidal material of any sort is added to a coagulated hydrogel, such as clay, the emulsoid possesses the power to peptizate or deflocculate the clay hydrogel, thus rendering it capable of colloidal suspension. By their reversible and protective influence humous materials hinder the coagulation of clay colloids; by their deflocculating influence they tend to make the hard, dry, sun-baked clays again reversible.

The terms humus and humic acid have been mentioned. The latter is a very complex substance of doubtful composition; it is an acid and possesses a colloidal nature. It dissolves in 8,337 parts of water at 6°. Its ammonium and magnesium salts are rather easily soluble; calcium humate dissolves in 3,125 parts of water, while the least soluble ferric humate dissolves in 5,000 parts. The humic acids are solvents for silica. Humic acid has the property[1]

[1] Julien, "On the Geological Action of the Humic Acids," *Proc. Amer. Assoc. Adv. Sci.* (1879), pp. 311–410.

of gluing together vegetable earths into layers impervious to water. Their action consists mainly in the removal of calcium, magnesium, and iron, which are again precipitated at the lower limit of action, either by soluble salts, by exchange of bases, or by loss of water. The precipitated organic humus is finally oxidized and disappears, depositing the base metals as hydroxides or carbonates.

Summary of the mineral constituents of the soil solution.—In summarizing, the mineral matter of the soil solution may be divided into two classes. The more easily diffusible are those comprising the soluble alkali salts, the soluble acid-carbonates of calcium and magnesium, the slightly soluble ferrous compounds, the ferric humates, and the semi-colloidal sodium and potassium silicates. The less easily diffusible are the colloidal gelatinous silicic acid, the gelatinous hydrated silicates, and the colloidal hydrated ferric oxide. The solvent action of the alkaline-soil solution and of the humic acids, aided by the abrasive effects of the earth's displacements, slowly but surely transform the quartz pebbles into colloidal silica. Under the influence of the decaying organic matter the ferric compounds are reduced, temporarily at least, to ferrous compounds. While the existence of ferrous compounds in contact with the oxygenated soil atmosphere must obviously be a short one, the alternate oxidation and reduction permit the slow downward transportation of iron. The decomposition of the original complex aluminum silicates leads ultimately to the formation of the colloidal hydrated aluminum silicates. These are the most complex, most resistant, and the least soluble of all of the decomposition products produced by the disintegration of silicate rocks.

Hence in the leaching of the so-called weathering products of the original glacial till one should expect to find a gradual relative increase in the proportion of the soluble diffusible materials from the surface downward. On the contrary, conditions permitting, a gradual decrease in the proportion of alumina should be observed. This is exactly what is found from a study of the results of the chemical analyses of a complete series of strata in any single complete cut.

The kinds of materials analyzed and the localities from which they were taken.—The kinds of materials analyzed and the localities from which the materials were taken are as follows:

A. Kansan gumbotil, and oxidized and leached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster in the southeast corner of Monroe County, Iowa.

B. Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.

C. Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.

D. Illinoian gumbotil, oxidized and leached Illinoian till, and oxidized and unleached Illinoian till from bluff north of Fort Madison, Lee County, Iowa.

The complete sections at each of the foregoing localities have already been given in this paper, but it seems well to bring them together here in relation to a discussion of the chemical analyses of materials:

A. Section in cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous	2	
4. Loesslike clay, chocolate-colored, leached	1	6
3. Loesslike clay, light-colored, grayish, on dry surface looks like gumbotil, has chocolate-colored stains, sticky when wet, contains a few small siliceous pebbles, leached	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starchlike fracture when wet; leached	12	
1. Glacial till (Kansan), brown in color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish-yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut	5	

B. Section in cut on the Chicago, Milwaukee & St. Paul Railway at mile 372, one mile west of Murray, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color on dry surface with irregular lines of brown; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy	15
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions	11

C. Section in cut on Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County, Iowa:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions	7	
Unleached loess, lighter-colored on dry surface than the leached loess, and when damp it is buff with gray streaks. Contains shells and concretions	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray drift with a few pebbles. It is gumbotil-like but effervesces freely. It was probably picked up from the gumbotil zone below	5	
4. Soil band containing carbonaceous material		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper six feet is fine-grained, gray, and is less sticky and gumbotil-like than the lower seven feet, which is leached, but has some calcareous concretions	13	

	Feet	Inches
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide.....	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp, many calcareous concretions, expecially in upper ten feet.....	17	

D. Section in bluff north of Fort Madison, Lee County, Iowa:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow.....	7	
3. Gumbotil (Illinoian), drab to dark color; starchlike fracture; few pebbles; leached....	4	6
2. Glacial till (Illinoian), oxidized, leached....	6	
1. Glacial till (Illinoian), oxidized, unleached to base.....	15	

Chemical analyses of the Nebraskan, Kansan, and Illinoian gumbotils and their substrata.—The analytical data obtained from the chemical analyses of samples taken from localities at "A," "B," "C," "D" have been collected in the following tables. The results are given in two forms, (*a*) the percentage composition with respect to the less mobile constituents, (*b*) the parts by weight of these constituents per 100 parts of the more resistant Al_2O_3.

TABLE I

A. Chemical analyses of Kansan gumbotil and oxidized and leached Kansan till from cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster, in the southeast corner of Monroe County, Iowa.

	a) Percentage Composition				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Kansan).....	72.03	4.18	12.27	1.33	2.29
Glacial till, oxidized, leached..	73.11	4.62	11.57	1.66	2.56
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Kansan).....	587.0	34.10	10.84	18.68	
Glacial till, oxidized, leached...	631.9	39.92	14.35	22.18	

TABLE II

B. Chemical analyses of Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.

	a) Percentage Composition				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Kansan)	70.46	4.17	12.04	1.21	0.55
Glacial till, oxidized, leached	71.84	4.62	10.86	1.29	0.72
Glacial till, oxidized, unleached	68.56	4.40	11.13	4.48	0.79
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Kansan)	585.2	34.7	10.05	4.57	
Glacial till, oxidized, leached	661.5	42.5	11.87	6.66	
Glacial till, oxidized, unleached	616.0	39.5	40.30	7.16	

TABLE III

C. Chemical analyses of Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.

	a) Percentage Composition				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Nebraskan)	71.59	4.35	12.79	1.26	0.93
Glacial till, oxidized, leached	66.85	5.92	11.65	3.67	0.78
Glacial till, oxidized, unleached	66.52	4.80	11.18	4.28	1.43
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Nebraskan)	559.7	34.0	9.90	7.31	
Glacial till, oxidized, leached	573.8	50.7	31.51	6.71	
Glacial till, oxidized, unleached	594.5	42.9	38.30	12.81	

Table V shows the comparative results of the chemical analyses of "A," "B," "C," "D."

Discussion of the chemical data.—The three localities "A," "B," and "D" show the gumbotil underlying loess or loesslike clay covered by a thin layer of soil. At "C" the Nebraskan gumbotil lies below soil with no intervening loess or loesslike clay. The

TABLE IV

D. Chemical analyses of Illinoian gumbotil, oxidized and leached Illinoian till, oxidized and unleached Illinoian till, from bluff north of Fort Madison, Lee County, Iowa.

	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
	a) Percentage Composition				
Gumbotil (Illinoian)	71.07	4.24	14.91	0.79	0.85
Glacial till, oxidized, leached	72.24	7.43	11.65	0.61	0.95
Glacial till, oxidized, unleached	72.30	3.47	8.59	4.13	1.28
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Illinoian)	476.0	28.44	5.34	5.68	
Glacial till, oxidized, leached	620.1	63.80	5.26	8.22	
Glacial till, oxidized, unleached	841.2	40.39	48.10	14.95	

TABLE V

	A	B	C	D
	SiO_2			
Gumbotil	72.03	70.46	71.59	71.07
Glacial till, oxidized, leached	73.11	71.84	66.85	72.24
Glacial till, oxidized, unleached	.....	68.56	66.52	72.30
	Fe_2O_3			
Gumbotil	4.18	4.17	4.35	4.24
Glacial till, oxidized, leached	4.62	4.62	5.92	7.43
Glacial till, oxidized, unleached	.....	4.40	4.80	3.47
	Al_2O_3			
Gumbotil	12.27	12.04	12.79	14.91
Glacial till, oxidized, leached	11.57	10.86	11.65	11.65
Glacial till, oxidized, unleached	.....	11.13	11.18	8.59
	CaO			
Gumbotil	1.33	1.21	1.26	0.79
Glacial till, oxidized, leached	1.66	1.29	3.67	0.61
Glacial till, oxidized, unleached	.....	4.48	4.28	4.13
	MgO			
Gumbotil	2.29	0.55	0.93	0.85
Glacial till, oxidized, leached	2.56	0.72	0.78	0.96
Glacial till, oxidized, unleached	.....	0.79	1.43	1.28

loess and loesslike clay are of great interest but are not being considered except incidentally in this paper. In places these materials are clearly eolian in origin. In other places the loesslike clay may be related closely in origin to the gumbotil. The presence of loess or loesslike clay above the gumbotil might be expected to have had some slight effect upon the present chemical composition of the gumbotil, and in fact may explain the few percentages in the analyses which might seem to contradict the theory proposed.

It is assumed that the composition of the flour of the unoxidized and unleached till is now the same as it was when laid down by the glacier. The possibility exists, however, that it may have received a small amount of leached material from above, or that it may have lost to the strata above by capillary flow slight quantities of the more easily diffusible dissolved materials. It is not to be expected that its composition will be similar to that of overlying materials which have been subjected to marked chemical changes, to leaching, or to infiltration.

Attention should be called again to the fact that the gumbotils occupy definite topographic positions and that, as a result of erosion subsequent to the formation of the respective gumbotils, the areas of gumbotil are now very limited compared with the extent of the former gumbotil plains.

A study of Tables I to IV will bring out several interesting facts. In all of the series here represented the percentage of Al_2O_3 decreases downward from the gumbotil through the oxidized and leached zone. Except in the case of "B" (Table II), this decrease continues also through the oxidized and unleached zone.

Perhaps the most important evidence in favor of the leaching theory is to be gained from a study of the relative proportions of CaO and MgO in the various horizons. In practically every series the proportions of these two constituents show a pronounced increase downward. Apparent contradictions for both might be considered for MgO in Table III and CaO in Table IV. Field relations will show in these instances either that the gumbotil is overlaid by material containing a higher proportion of these constituents, or that erosion began before the leaching process in the gumbotil was completed. Assuming that the loess or the loesslike

clay is a subsequent formation, it also will have been leached of some of its CaO and MgO. This means a slight increase in the proportions of these two in the stratum below, the leaching of which has not been completed.

The leaching process.—The silica and iron are less diffusible and hence less subject to leaching than are the carbonates of calcium and magnesium, and a much longer time is required for complete leaching. In every instance the proportion of iron in the gumbotil is less than it is in the oxidized and leached stratum just below. Except for the case of the Nebraskan (Table III), the proportion of SiO_2 is greater in the oxidized and leached stratum than in the gumbotil. It should be observed that the Nebraskan at locality "C" underlies the Kansan, and the apparent discrepancy may be accounted for in the transfusion of the alkaline silicates from the Kansan into the upper strata of the Nebraskan below. On the basis of parts per 100 parts of Al_2O_3 not only CaO and MgO but also SiO_2 show distinct evidence of leaching even in the oxidized and leached zone, and this is true for practically every series. On the same basis the evidence points to a leaching of the iron into the oxidized and leached zone from the gumbotil, but the time allowed was not sufficient for the subsequent leaching of the iron from the oxidized and leached zone into the one below. This is not surprising, since, as will be shown later, the iron is the last constituent to be leached away.

The oxygenated and carbonated water falls upon a uniformly level, more or less uniformly constituted, blue to blue-black drift. Percolating downward, it dissolves a portion of the rock material. Hydrolysis follows, and there are liberated successively the hydroxides of sodium or potassium, then of calcium or magnesium, and finally the more or less difficultly soluble hydroxides of ferrous and ferric iron, depending upon the nature of the iron in the original silicate. The ferrous iron throughout the depth penetrated by the dissolved oxygen is immediately oxidized and the deposit assumes the typical iron color of the yellow clays.

The calcium and magnesium hydroxides combine with the carbon dioxide of the soil atmosphere to form the insoluble carbonates. These crystallize out as calcareous concretions. The

soluble alkalies and the alkaline silicates are carried downward by the moving free-water. The negative colloidal silicates and silicic acid are coagulated and thus rendered motionless by the positively charged calcium and magnesium ions. As hydrolysis proceeds the mass of the insoluble material thus formed increases and probably does continue to increase until all of the easily available, hydrolyzable materials are used up or removed.

The second stage of the leaching process now follows. Obviously those insoluble substances which are most easily attacked will be the first to be leached away. These are the carbonates of calcium and magnesium. Although only very slightly soluble, the dissolved portions of these combine with the carbonic acid of the soil solution to form the soluble acid carbonates. These are carried downward to lower levels, where in fissures and crevices they again crystallize as irregular concretions. In this way were formed all of those calcareous concretions which are found in the oxidized zone.

According to the law of mass action, the activity, or the solvent effect, of the carbon dioxide will be greatest at points where its concentration is a maximum. This obviously will be at the upper level of the initially unleached calcareous zone. Owing to its diffusion power some of the carbon dioxide may escape combination at the upper level only to combine at a slightly lower level. Ultimately there will be a lower limit beyond which the carbon dioxide entering from the atmosphere will not penetrate, or its concentration in the soil solution will be too slight to produce any appreciable chemical effect. These two limits of maximum and minimum activity represent the boundaries of the dynamic zone of carbonic acid activity—the oxidized and leached zone. As time goes on the concretions at the upper level disappear, and the levels of maximum and minimum activity move downward simultaneously.

This dynamic zone has played an important rôle in all drift transformations. It spreads horizontally like a continuous sheet of more or less uniform thickness. It is found always directly upon the oxidized and unleached drift and directly below the gumbotil. In the Nebraskan drift it is thin, less than two feet to somewhat more than four feet. The oxidized leached zone of the

Kansan drift averages about five feet, attaining in a few places a thickness of about seven feet. That of the Illinoian has an average thickness not to exceed six feet.

After the leaching of the calcium and magnesium carbonates there follows a third step. When the concentrations of the precipitating calcium and magnesium ions have been reduced below their critical coagulating values new processes occur within the leaching zone. The coagulated iron passes into solution either as colloidal ferric hydroxide by peptization or deflocculation by the emulsoidal organic humous material or through the influence of peptizing ions, or as ferrous compounds by reduction by organic matter. Thus, either by colloidal flow, by alternate reduction and oxidation, or through the medium of its soluble or slightly soluble salts, the iron is leached and slowly passes downward. The silica either in the form of the colloidal gelatinous silicic acid or as the alkaline silicates also moves downward. Likewise, through various peptizing influences the colloidal clays and the simpler colloidal silicates begin to swell and deflocculate. Ultimately some of these pass into suspensions of colloidal particles. They are caught also in the downward current and carried by it to lower levels, where they are again coagulated. Only a very slight amount of this kind of material is leached away. There is left above only the more resistant, less mobile, complex colloidal aluminum silicates.

The stratum now forming, deprived of practically all of its sodium and potassium, of most of its calcium and magnesium, and some of its iron and silica, is the present residuum of the whole chemical leaching process. This is the gumbotil.

Physical and chemical properties of the gumbotils.—The properties of the gumbotil are largely those which one might predict from a knowledge of the colloidal chemistry of clays. Like certain colloids it becomes very hard and tenacious when dry; it swells when wetted and then to some extent passes spontaneously into colloidal suspension. It becomes sticky and sometimes so slippery that under the pressure of the earth above it oozes or slides out of the sides of the hills. It is gray when dry, dark when wet. The characteristic color changes of the gumbotil are those imparted to it

by the colloidal clays, perhaps the kaolin contained in it, the color of the colloidal material being sufficiently strong to mask the reddish-yellow color of any oxidized iron which may be present. This doubtless is responsible for the belief held by some persons that the iron in the gumbotil is deoxidized or reduced, a condition which could hardly be possible in the presence of the oxygenated soil solution.

The chemical analyses of the gumbotils from different drifts and localities show, with respect to certain constituents, a striking similarity. This is especially true for the iron and silica and, as we might expect, for the calcium. Slight fluctuations may be expected due to differences in the nature of the original rock materials, to the amount of rainfall, or to leaching from above. It may be concluded, therefore, that all gumbotils have a common origin—the chemical modification by weathering of glacial till.

Similarities of the gumbotils and the adjacent yellow oxidized and leached zones.—Furthermore, the chemical analyses, as arranged in Table V, show a slightly less striking similarity between the gumbotil and the yellow oxidized-leached clay. Naturally one should expect to find a slightly greater concentration of the diffusible material in the leached zone. One should expect also to find a slight variation in the proportion of any one constituent between the top and the bottom of any single zone. Each level in any one zone is still slightly unleached with respect to another level close to and above it.

The proportions of most of the constituents present in the oxidized-leached and gumbotil zones differ in most of the series by only a few tenths of 1 per cent. When greater deviations occur it can be shown that one or more of the upper strata have been removed before the leaching process was completed. The distinguishing features between these two strata are, therefore, due primarily to differences in the physical properties, and these properties are chiefly the colloidal properties of the clay itself. It is possible that two forms of the same material are being dealt with, namely, the gumbotil, a highly colloidalized form, and the oxidized-leached clay, the non-colloidalized form, that is, a form which in the presence of electrolytes is incapable of assuming

certain colloidal properties. In fact recent uncompleted work by Mr. L. B. Miller[1] gives evidence which not only supports the idea that these two zones differ chiefly in respect to differences in colloidal properties but also strongly confirms the theory that the gumbotil is directly related to the drift. It has already been stated that colloidal properties are primarily properties of the surface. A given colloid. material of different degrees of subdivision will adsorb varying amounts of a given substance, and the amounts adsorbed by a given mass of the colloid will be approximately proportional to the specific colloidal surface. Assuming that hygroscopic water adsorbed by clays may be taken as a measure of colloidality and of surface development, Miller has determined the amount of hygroscopic water taken up by each of these clays at 25.° He has found that, beginning with the original drift material the specific surface increases gradually, but at an increasing rate upward to the gumbotil. He has also determined the "total-water capacity," that is, the amount of water per gram which is just sufficient to cause the clays to "run." This likewise is greatest for the gumbotil in any drift, and it decreases gradually downward through the lower layers. The high "total-water capacity" of the gumbotil accounts for the ease with which it slides in exposed cuts.

SUMMARY

The aim of this paper has been to show by field and laboratory evidence that the gumbotils on Nebraskan, Kansan, and Illinoian glacial tills are the result chiefly of chemical weathering of drift. Thus far no distinctive evidence has been found in Iowa to indicate that the bowlder clay from which gumbotil is thought to have been derived differed to any great extent from typical bowlder clay. In the case of the Iowan and Wisconsin glacial tills, which are too young to have had a gumbotil developed on them, the till at and near the surface does not appear to differ in any important respects from the till which is deeper below the surface. In this connection it should be stated that Mr. E. W. Shaw, as a result of his studies of the Illinoian drift in southern Illinois, the Kansan drift in

[1] L. B. Miller, *The Colloidal Properties of Clays.*

northern Missouri, and other till sheets elsewhere, believes that the upper parts of the tills have been, from the times of deposition of the drifts, somewhat different from the middle and lower portions of the drift.[1]

It should be stated that, although it is believed that gumbotil is essentially the result of chemical weathering of glacial till, it is recognized that wind action, freezing and thawing, burrowing of animals, slope wash, and other factors may have contributed to the formation of these gumbotils.

In a subsequent paper attention will be directed to the fact that the gumbotils, on account of their distinctive characters, wide distribution, and topographic positions, are the most satisfactory criteria that have yet been found for differentiating the older drifts. Furthermore, since the gumbotils are the result of changes which took place in interglacial times, they may be considered in relation to the problem of the relative durations of the interglacial epochs.

The gumbotils strengthen the view now generally accepted that the history of the Glacial Period involves, not a few thousand years but probably hundreds of thousands, and possibly millions, of years.

[1] E. W. Shaw, "Characteristics of the Upper Part of the Till of Southern Illinois and Elsewhere," *Abstract, Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 76.

DIASTROPHISM AND THE FORMATIVE PROCESSES

XI. SELECTIVE SEGREGATION OF MATERIAL IN THE FORMATION OF THE EARTH AND ITS NEIGHBORS

T. C. CHAMBERLIN
University of Chicago

In the last number of this *Journal*[1] I endeavored to deduce from a comparison of the earth with Mars, Venus, and the moon, the order of magnitude of the total shrinkage suffered by the earth. The results proved surprisingly large. Not only that but they seemed to show that the shrinkage per unit of mass-increase became greater as the total mass grew. Since small bodies have but feeble gravitative ability to gather and hold the lighter order of molecules in a free state, it seemed probable that the moon and Mars contain higher proportion of the heavy molecules than Venus and the earth. This seemed to add emphasis to the high densities of Venus and the earth compared with the moon and Mars. It appeared to strengthen the presumption that, in this group of bodies at least, the degree of density was due to the concentrating effect of superior mass rather than original heaviness of material.

However, final conclusions were held in abeyance until the modes of organization of the four bodies could be studied with a view to detecting the probable laws of their segregation in so far as these affect the proportions of inherently light and inherently heavy materials. It is this inquiry that forms the theme of the present paper.

The subject necessarily reaches back to the genesis of this group of bodies, and the discussion will need to concern itself quite as much with the dynamic environment that influenced their formation as with the material that entered into it. The

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from a Comparison with Mars, Venus, and the Moon," *Jour. of Geol.*, XXVIII (1920), pp. 1–17

study need not, however, go much beyond the conditions that determined the amount and nature of the material, the mode of aggregation, and its physical state. It must be specific enough, however, to touch the conditions that controlled the relative proportions of inherently heavy and inherently light material. It is therefore necessary to consider with some care the basic laws of organization of such bodies so far as these bear on selective segregation. It will save time and help toward clear treatment to give at the outset what seem to me to be the more essential principles that control the formation of cosmic bodies. It will not be amiss if these are made rather sweeping, provided they are definite enough to apply to the particulars required by our problem.

PRELIMINARY CONSIDERATIONS

While the four bodies named will usually be in mind when other bodies are not specified, there will be occasion to use certain terms in other than their commonest senses, and so let us agree upon these at the outset. By cosmic units let us understand, not simply celestial bodies, but organized bodies of any kind, whether large or small, whether "organic" or "inorganic," provided they serve a unitary function in natural processes. Let us recognize that these range from the atom, whose organization is now being pursued with a skill and success worthy of the highest admiration, up through the molecule, the crystal, the chondrus, the colloidal unit, the cell, the biologic organism, the planet, the star, the star cluster, to the stellar galaxy, at least. Let these more salient types stand for the multitude of intermediary and divergent species of divers sorts that make up the full series. Let them also stand for the unknown extensions of the series downward and upward. Let us agree that the only essential of a cosmic unit is an individualized organization which has its own material center and its own dynamic province. These organized units of course enter into varied relations with one another and form a great complex superseries, but let us consider merely the features that are common to all because essential to all. Among these essentials should appear, in their true relations, those particular features we need to apply to the solution of our special problem.

The wide range of the category thus recognized implies that the study of the organization of cosmic units is not a theme which falls solely within the province of any one of the natural sciences as we now know them; it is common ground, belonging to each and all in so far as their problems reached back into it. The biologic student of the genesis and career of the iron bacteria may invade, of his own right and to any extent that serves his purpose, the Proterozoic terranes or any other terrestrial field that promises him evidence, and we of the geological school may not say him nay, however much we may claim the province as peculiarly our own in respect to our own problems. Each particular science is best suited to make certain inquiries into the origin of organisms and of organizations, and to yield certain contributions to the common science of cosmology, using the term in its broadest sense as the science of cosmic organization, in distinction from cosmogony, which in its original sense—the birth of the cosmos—belongs to philosophy, theology, and mythology.

The cosmic systems mount up by hierarchies from what seem simpler to what seem more complex, but in ultimate analysis all, even the atom, and perhaps even the electron, are themselves complex, and the depth of such complexity is at present unfathomable. This pervasive complexity puts all in a common class and, in some sense, simplifies the common cosmologic problem, for its essence lies in finding those principles of organization that are so far essential to any organization as to be common to all.

FUNDAMENTALS OF COSMIC ORGANIZATION

I. Every cosmic unit bears a dual aspect, a material organization, and a dynamic organization. In ultimate analysis these may be merely different phases of the same fundamental entity, whatever that may be, but in their sensible aspects they are distinctly diverse. The one is very tangible and impressive and has almost monopolized attention; the other is invisible in itself and has fallen much short of the recognition it deserves as an essential element in every cosmic organization. The first is too familiar to need emphasis here; the second requires all the emphasis which a neglected essential can well receive.

II. The material factor of every cosmic unit is not only pervaded internally but is surrounded by a field of force, dominantly attractive but partially repellant. In the present study, the sphere of dominating attraction—the sphere of gravitative control—will, for brevity, usually be spoken of as though it alone represented the dynamic element of the dual organization, for it is chiefly the outlying field of gravitative control that functions actively in the selective segregation of material in the formation of cosmic bodies.

The extreme theoretical reach of gravitation is indefinite, but within a certain portion of this indefinite field, the attractive force of the particular body under study is sufficient to give it immediate control over bodies inferior to itself, unless they carry kinetic energy of their own in sufficient amount, and properly directed, to insure their escape. This field of superior force constitutes the body's sphere of control.[1] It is necessary to note that this control is merely *immediate* control; there are usually, perhaps always, higher types of control which hold ulterior sway over these, but this superior sway is exercised in such a concurrent way as not to prevent the immediate control essential to the minor body as a condition of its own existence and perpetuity. These higher controls may spring from some single more massive body or from some composite organization, as a star group. The superior spheres of control envelop the minor spheres of control; thus the moon's sphere of control revolves within that of the earth; the earth's sphere of control revolves within that of the sun; the sun's sphere of control revolves within the sphere of control of the "local cluster" of stars, and this in turn within the sphere of

[1] The recognition that cosmic bodies are surrounded by spheres of gravitative control is not at all new but merely neglected; Laplace worked out "the spheres of activity" of the planets—here called spheres of control to avoid confusion with the indefinite outward extension of the influence of the cosmic body. The spheres of control of the planets have been worked out more recently on a different basis by Moulton (*Popular Astronomy*, No. 60, May 15, 1899). The spheres of equal attraction, a different matter, have been worked out by the senior Asaph Hall (*Popular Astronomy*, April, 1899). The concept of a sphere of control is herein given a wider application than is common, and is assigned an essential function in the organization and maintenance of cosmic bodies. The concept is regarded as a helpful means of research, particularly as an aid to visualization.

control of the stellar galaxy. The sphere of control of the atom enters into the sphere of control of the molecule, and that into higher orders in succession up to the earth and beyond. The whole cosmic scheme seems to be a system of such hierarchies whose limits in either direction are unknown.

III. The dynamic value of each sphere of control dies rapidly away from the mass in which it centers to its outer border. Not only this, but each sphere of control that revolves within a superior sphere of control is larger or smaller, more effective or less effective, according to its position within such superior sphere of control. It is likely to be either increasing or diminishing as the body in which it centers swings through its orbit. If it were made to constantly approach the controlling body, its extent and efficiency of control would grade entirely away to extinction before such superior mass was reached.

IV. In such spheres of control as center in single great masses, the differential pull of the controlling mass becomes so great relatively, in its innermost portion, that bodies of a minor order intruding upon it are liable to be disrupted. When the approaching minor bodies are gaseous, their spontaneous tendency to dispersion insures their dissipation. When they are solid, the degree of fragmentation to which they are subject is likely to be limited to certain sizes, for as the fragments grow small the strength of their cohesion increases relative to their mass. Cohesion is not likely to be important in large bodies because they are usually self-compressed and hot within to such a degree that their tendencies to expand, when pressure is relieved, usually surpass their coherence.

The outer border of the disruptive zone is known as the Roche limit. Its determination by Roche was based on an ideal homogeneous fluid satellite approaching an ideal homogeneous fluid planet of equal uniform density, cohesion being neglected. He fixed the limit of disruption at 2.44 times the radius of the planet.[1] This limit is in close accordance with what seems to be the realized result in the case of Saturn's rings which stand as the classic example of minute division and distribution in response to this disruptive effect. The mathematical conclusions of Roche were amply

[1] Edward Roche, *Memoirs de l'Académie Montpelier*, I, p. 243.

supported some years later by the studies of Clerk-Maxwell,[1] and their common results were afterward verified by the spectroscopic observations of Keeler, who demonstrated that the rings are formed not of gas, as once supposed, but of discrete particles revolving in independent orbits, in other words are minute satellites or satellitesimals. From a recent study of the albedo of the rings, Bell has concluded that the largest masses in them probably do not exceed three meters in diameter—at least they are not more than a few meters across—while the majority of the visible particles are very much smaller, ranging down to the dimensions of wave-lengths of light.[2]

For the immediate purposes of our study, the important point is not so much that bodies entering this zone of disruption either from without or within are reduced to relatively small particles, though this is important, as that these conditions of stress from the controlling body stand in the way of the organization of any new body within this zone. So far as the aggregation of independent bodies of any notable mass is concerned, this is an inhibitive zone. Considered with reference to the controlling body, it may perhaps be said to be a protective zone, tending to preserve its isolation, independence, and undivided sovereignty.

In view of uncertainties as to the precise qualifications the Roche limit might require in the case of a rotating nebular spheroid, Moulton worked out a limit of similar nature but on a different basis, the purpose of which was merely to fix a more certain limit within which the organization of nebulous matter would be inhibited.[3] This limit was placed at 1.38 times the radius of the nebular spheroid, or a little more than half the radial extent of the Roche limit.

V. Accepting as a working basis the Newtonian doctrine of the unlimited penetration of the force of gravitation, it is a logical deduction that all space is under the immediate domination of

[1] "On the Stability of Motion of Saturn's Rings," *Scientific Papers of James Clerk-Maxwell*, Vol. I, pp. 288–375.

[2] Louis Bell, "The Physical Interpretation of Albedo, II. Saturn's Rings," *Astrophysical Journal*, L (July, 1919), pp. 1–22.

[3] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), pp. 122–26.

some dynamic organization or some combination of such organizations, except perhaps that theoretical neutrality may arise momentarily on the border lines of spheres of control where exact balancings of attraction may obtain for an instant; but as all celestial bodies are moving relative to one another this can only be transient and unimportant. The concept of such pervasiveness of stress throughout all cosmic space has the merit of dismissing from serious consideration certain inherited notions, for example, that somewhere in space there may be regions where "primordial" matter may have lurked in idleness from a supposed beginning, or where nebulous matter, or dissipated particles of any sort, may somehow assemble purely under their own attraction and later drift into the active cosmic world as quasi-primordial matter, and similar notions that seem to be but reshaped vestiges of oriental concepts of primitive chaos. A much more important function of the deduction, however, is its amplification of the doctrine of dynamic encounter.

VI. From the preceding generalizations it follows that the spheres of control of cosmic bodies are either perpetually plowing through the higher orders of spheres of control that envelop them, or are impinging upon other spheres of control of their own type. In either case, their own domains, as well as those of the bodies with which they interact, are perpetually suffering encroachments. Innumerable dynamic encounters of widely varying types and moment thus spring from cosmic movements. As an incident of these innumerable encroachments of one domain upon another, transfers of the minuter class of units from the field of dominance of one controlling center to that of another are almost perpetual occurrences. They constitute a system of exchange of the first order of extent and seem to be a vital factor in cosmic life. In the case of the earth, revolving in the sphere of control of the sun, this system of exchange is regarded as having a very high order of importance in the maintenance of our atmosphere and the increase of our hydrosphere.

Since encounters of some order of importance are almost infinitely frequent, it is necessary to specify explicitly the nature of the encounter in any argument that is based on frequency of

encounter. Furthermore, in determining the frequency of a given class of encounters, it is not sufficient to postulate an artificial case convenient for computation, for actual cases usually involve a natural selective adjustment of associated bodies with reference to one another. And further, the present deployment of stars may not be identical with that of earlier ages. And still further, if the frequency has for its criterion a given effect or is to be considered with reference to a given effect—explosive action for example—susceptibility to such effect is as important as the nature of the encounter. These requirements are commonly neglected.

VII. All cosmic organizations seem to be the products of opposing elements. The balance between these opposing factors seems to form the critical issue on which their endurance depends. These opposing factors vary with age, state of growth, environment, and other conditions. Out of these variations of balance arise stages of increase and depletion, of partial or total disorganization and regeneration. The history of the cosmos seems to be essentially a succession of cycles arising from either internal or external disturbances of balance. Interestingly enough, the atom happens just now to afford one of the best illustrations of internal disturbance leading to transition in organization. Thought until recently to be beyond the utmost resources of disintegration, it is now known that some of the heaviest atoms are undergoing "spontaneous" disorganization. By way of offset for the old error, as it were, the dictum now is that no known device, appliance, or force can stop this disintegration. Future inquiries will probably disclose the golden mean between these extremes. In spite of all disintegrating influences, the integrity of atomic organization, in the main, is maintained to an extraordinary degree. In the larger cosmic world there are intimations of analogous "spontaneous" disintegrations standing over against similar persistency. The eruptivity of the sun, on which the planetesimal hypothesis is founded, is revealing striking analogies to the partially disintegrating atom as will be detailed later. Some of the great hot stars give intimations of a very delicate balance of internal forces. Over against the enormous concentrating force of gravity and its allies, stands the scarcely less potent alliance of the forces of dispersion. These

latter seem, on the whole, to be overmatched by their opponents, as implied by the very existence of the stars; and yet the forces of dispersion are clearly successful in particular ways, as, for example, in the matter of radiations and in some loss of high-speed molecules and of electrons.

In this state of wavering balance between internal contending forces, those great seething bodies are plunging at high velocities through what, in a material sense, is an approximate vacuum, but what, in a dynamic sense, is an approximate plenum, a plexus of lines of force of almost infinite complexity. They are thus speeding through a perpetual succession of contingencies of external disturbance. Their hold upon their own material hangs on the perpetuated superiority of their concentrative forces, expressed typically but not wholly in their spheres of gravitative control over their dispersive forces. If the controlling spheres are invaded in a shallow way there is likely to be only trivial loss; if they are invaded deeply, serious disintegration is the logical effect. It is important to note that this disintegration is a joint effect, as much due to the approximate balance of the internal forces as to the disturbing power of the external forces.

And so in dealing with phenomena of this class, it is not more important to inquire into the direct action of the external agencies than into the state of balance of the powerful forces within these supremely active organizations themselves. This is the more imperative because there is growing reason to believe that certain orders of stars are at or near the limit where growth in mass is overmatched by concurrent growth in dispersive forces. If this belief is well founded, such nearly balanced giants of the skies may be regarded as peculiarly susceptible to disturbances of equilibrium arising from the intrusion of foreign dynamic influences into their domain, or perhaps equally their own penetration into areas of concentrated stress arising from special marshallings of other great bodies.

These considerations are deployed at some length here because the stellar conditions that render dynamic encounter effective are too commonly overlooked, and because these conditions are vital in considering cosmic disorganization which in turn is regarded as a step necessarily precedent to cosmic reorganization.

VIII. There is pressing need for rectified concepts of cosmic time and stellar endurance. The recent deep penetration of the stellar field by improved instruments, increased skill, and new methods has forced a revolutionary enlargement of concepts of interstellar space, while co-ordinate enlargements of concepts of cosmic time have not kept apace. And yet time and space are necessary correlatives in stellar movements and in stellar organization. Time concepts must keep pace with space concepts if consistent views of organizing processes are to be entertained. Inadequate concepts of time retained from old estimates of the sun's longevity and like sources now embarrass the free acceptance of cosmic views—if these imply great intervals of time—much as they restrained geological interpretations during the last century. It may be wholesome therefore to inquire specifically: What length of life is implicitly assigned to stars when they are made integers in the evolution of a globular cluster or of a galaxy? What intergenetic periods mark off the generations of stars? What careers appropriately fit them into the vast cosmos that is now revealing itself? And then, subordinate perhaps to the life of a star, what intergenetic periods mark off the generations of planets?

It is to be recognized, of course, that the career of a planet may belong to a different order of magnitude from the career of a star, or of a star cluster, or of the galactic system, and no doubt these differ among themselves. And so our immediate problem may not be more than remotely concerned with these immense questions, but yet it is related to them, and its answer should be consistent with them. Perhaps all that need be said here is that when the estimates of the longevity of stars, star clusters, and the stellar galaxy are brought into harmony with the time requirements of their own processes of organization and their own normal careers, students of the evolution of our little planet will probably feel quite as much call to amplify as to repress their interpretations of the terrestrial time factors in order to bring them into harmony with those of the higher systems.

IX. As a matter of scientific conservatism, it should be taken for granted that the sole source of material and of energy for the formation of new organizations is to be sought in the dissolution

of pre-existent organizations. In most cases, if not in all, however, the dissolution of such previous organizations is not ulterior dissolution; it is usually only the disintegration of one order of organization into elements of a somewhat lower order. Neither dissolution into chaos, in any strict sense, or into ultimate factors, nor generation from chaos or from ultimate factors or from anything that is absolutely new, seems to have any naturalistic warrant so far as present cosmic processes are concerned. Nor is there much more warrant for bringing into play any really unknown force or agency, though the discovery of new ways of action of known forces and agencies is to be expected. Scientific inquiry in genetic lines appears therefore to have for its appropriate field of study little else than partial disorganization followed by corresponding reorganization, though not necessarily of the same type, order, or extent. The scientific student therefore hesitates to call into service any material or energy which he cannot trace back to some known source.

X. In the formation of new cosmic bodies, even of the "inorganic" class, an organizing germ or nucleus, inherited from some parent organization, seems to have much the same function, and to be about as necessary as the seed or the ovum of an organism of the "organic" type. In either case the germ must apparently have both a material and a dynamic factor. This necessity appears to be chiefly due to the essential part which a collecting field of force and a retaining sphere of control play in organizing a cosmic body. In the concrete discussion to which we shall now turn, the strength and the reach of the organizing field of force will be held to be the chief criterion that determines whether dissevered or disorganized masses of matter shall reorganize as single bodies and pursue independent careers, or shall continue to be merely scattered food to be picked up by bodies already organized and endowed with effective collecting fields of force.

THE SELECTIVE SEGREGATION OF PLANETARY MATERIAL

In this discussion there will be no occasion to consider any hypothesis of the origin of the four bodies under study that has not been worked out into such definite terms as to bear specifically

on the question of the segregation of inherently heavy from inherently light material, the crux of our problem. Two postulated origins may clearly have such bearings, both of which are now familiar: (1) derivation from a rotating nebular spheroid by centrifugal separation brought into effective action by cooling and consequent acceleration of rotation, and (2) derivation from solar material ejected either spontaneously or under the stimulus of a passing body. The principles involved in these two types will probably serve to cover any other origin for which good reasons may be assigned.

While I am unable to see how planets such as form our system can have arisen from a rotating spheroidal nebula by centrifugal action, it yet seems best, out of deference to any who may still think that some view of this general type is tenable, to discuss this postulated mode of genesis in so far as it bears on our problem. It will only be necessary, however, to review the phase of the theory most dependent on the dynamic environment which controlled the evolution, for that touches the soul of the subject.

THE CENTRIFUGAL EVOLUTION OF A GASEOUS SPHEROID UNDER ITS OWN DYNAMIC ENVIRONMENT

Every organized nebula, like every other organized body, must have an adequate enveloping field of force and sphere of control as a necessity of its organized existence (I and II, above). The postulate that there was once a spheroidal nebula of the mass of the solar system which in contracting shed secondaries at various distances from its center as far out as $2\frac{1}{2}$ billion miles and yet was able to hold them then and afterward, carries the implicit assumption that it had a distinctly effective sphere of control. The shedding of the four little bodies under study took place only after the postulated nebula had shrunk to about one-twentieth of the radius it had when it displayed its effective holding power by its control over the material shed for the planet Neptune, while the outermost reach of its holding power must have extended much beyond this. At the relatively concentrated stage when the shedding of the substance for our little group of bodies took place, the inner zone of control must have grown relatively intense; the

disruptive belt just outside the rim of the rotating spheroid (IV above) must have had a notable development. If it were quite safe to assign it the full breadth of the Roche limit, which holds so well in the case of Saturn's rings, it would have had, taking the earth stage as a mean, an outward reach of 133,000,000 miles. But let us follow the safer course of using the conservative criterion of Moulton which gives a zone of 35,000,000 miles (IV above). Let it be recalled that the fragments of a disrupted mass revolving about the controlling body under the conditions of this case take orbital courses more or less parallel with one another. If the gaseous rim of the nebula could have been "thrown off" as a coherent body, it would not only have been disrupted into minute constituents, but these would have been given orbits of a type much like those pursued by the particles in Saturn's rings, all the more because the constituents of a gas tend to disperse themselves by their own interaction. This is equivalent to saying that the dynamic conditions within this zone were such as to inhibit any aggregation of this material into a common large body like the earth, Mars, or Venus, or into a lesser number of bodies of any considerable size. Even when such scattered orbital matter was left by the withdrawal of the nebula in the less intense horizons of the nebular field of force, its aggregation would still be greatly embarrassed by the superior control of the central mass. It is a common error to think of such scattered matter as though it were in neutral space entirely free from all forces except its own mutual attractions. The control of the central body so far embarrasses the assemblage of minute particles under the actual conditions of such a case as this as to render their aggregation into a single body improbable, as Moulton has so effectually shown.[1]

However, for the sake of seeing its bearings on the problem in hand, let us waive this improbability and try to follow the aggregation of the minute constituents of a quasi-Saturnian ring "thrown off" from the postulated rotating nebula.[2]

[1] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), p. 115.

[2] The deduction that the molecules shed by centrifugal action from a rotating gaseous spheroid would pass into individual orbits and form a planetesimal system does not depend solely on the Roche effect, as shown in "The Bearing of Molecular Activity on the Spontaneous Fission of Gaseous Spheroids," Publication No. 107, Carnegie Institution of Washington, 1909, pp. 161–67.

Let it be noted at the outset that the material to be aggregated was planetesimal in a very strict sense of that term. Each integer, whether it be a molecule, a particle, or any such more considerable aggregate as might be formed under the conditions of the case, was pursuing a nearly circular orbit around the central controlling body, the nebula at first, the sun later. This precisely fits the definition of a planetesimal. This means that the particles were in a dynamic, not a static state; they were under control, not free. Whatever aggregation followed was therefore of the planetesimal type, that is, particle joined particle in an individual way as their orbits and orbital forces permitted. Their orbital velocities hovered about that of the earth (18.6 miles per second) let us say, as a mean, the inner faster, the outer slower, the orbits of those equally distant from the center slightly inclined toward one another. Beside these differences of velocity and inclination—that arose from the nature of the case—the planetesimals inherited diverging courses from mutual collisions and rebounds as they emerged from the gaseous into the orbital state. To overcome these divergencies of orbit and these differences of speed and develop aggregates of one kind or another in place of the molecules inherited from the gaseous state, there were two classes of forces: (1) the collective attraction of the whole ring or disk or some bunched portion of it, and (2) the aggregating influences of individual molecules upon one another. The first would tend to make a single planet, if the whole were drawn together, or a few planetoids, if there was aggregation by bunching; the second would make at first a multitude of minute particles which would grow to larger sizes in proportion as the agencies of later aggregation proved superior to the effects of fragmentation, exfoliation, trituration, and friction in other forms after the particles had grown large enough to give these notable efficiency. Only the salient features can be touched here.

1. The ground of the first class of agencies has already been covered. No general nucleus nor any effective bunching was inherited from the nebula; indeed concentration was definitely inhibited up to the time of the withdrawal of the Roche limit. There might be, to be sure, a certain kind of transient bunching of the planetesimals in their orbits, such as affects the present planets,

but the relative rates of revolution that brought this about would destroy it. Collectively, the planetesimals would be so distributed that they would have almost no concentrating force of their own that was not later reversed or neutralized by their own orbital motions.

2. Practically the whole aggregation, then, would be that of the formation of discrete particles such as started with the joining of molecules and were built up thence into crystals, pellets, nodules, or whatever these might grow into later. The chemical combination of molecules would take place at proper temperatures readily enough by simple contact, whether this arose from collision while in the state of a gas, or from contacts brought about by planetesimal motion, or otherwise. Such refractory chemical compounds as now form the main mass of the solid bodies of the moon, Mars, Venus, and the earth, would probably be formed at high temperatures while they were still a part of the postulated nebula. The critical feature of the case lies in the way these complex refractory molecules would be gathered together after they were formed. While they remained in a free state as molecules they would normally tend to rebound on collision as molecules do and so maintain their free state. Even if they were brought together under conditions favorable to remaining together, their rotations or vibrations would tend to throw them apart, as would also subsequent collisions. To overcome these adverse influences, there was need for some special uniting agency, as is well recognized in the familiar case of the formation of the globules of fogs and clouds from water vapor in the atmosphere. It was long supposed that there must be a dust particle or some similar aggregate to serve as a collecting center (the "seed," X, above); but it was later found that molecules electrically charged serve this function also. In our problem, the formation of the first minute aggregates is the very crux of the question, and we cannot assume the existence of any such dustlike aggregates as the means of starting the process. But molecules electrically charged would probably be freely developed by friction, by the action of ultra-violet light, and by other means, and such charged molecules might well serve as the "seed" for starting the minute aggregates.

How far would such aggregation be likely to go, as a rule? There is no need to consider exceptional possibilities, for our problem relates to the common average result. The attraction between two molecules oppositely charged is many billion times greater than their gravitative attraction[1] and may be large compared with the inertia of their relative motion. Charged molecules might then serve as very efficient centers for the gathering-in of molecules, as also very small particles. But an electric charge is confined to the surface of a particle, which increases as the square of its radius, while gravitation varies as the mass which increases as the cube of the radius. And so, after a certain amount of growth, the charges carried on the particles would have less attractive power than the masses into which the particles had grown. But a more important practical consideration lies in the fact that electric charges of like kind repel one another and thus limit the total charge likely to be gathered on a given mass under natural conditions; for example, any electric charges which a forty-pound bolide would probably pick up naturally would lend little aid in gathering in other forty-pound bolides to form a forty-ton bolide. There is thus an obvious limitation to the range of effective electric aggregation, however efficient it may be as an originating agency. A beautiful illustration at once of such effective aggregation and of its limitation is presented by the formation of snow crystals from vapor in the air. These form and grow with great facility up to a certain size when the temperature of moist air falls below the freezing-point; but after a certain moderate growth, the limiting and adverse conditions increase in relative efficiency and arrest further growth; not infrequently it is reversed.

In the case of cosmic particles probably the most effective preventive of indefinite growth is the friction and collision of the masses, themselves. As the particles grow into nodules of notable size and mass, their cohesion is less effective relative to their moving force, and they more readily go to pieces on impact. Trituration and other lesser effects of moving contact would be more frequent

[1] R. A. Millikan, in a personal communication, states: "The attraction of two opposite electric charges is 10^{37} times as great as the gravitative attraction of two atoms of hydrogen."

and perhaps more effective on the whole than fragmentation. This would quite surely be true of the minute particles. According to the interpretation of Bell,[1] a milling process of this triturative sort has proved very effective in reducing to minute sizes the satellitesimals of the Saturnian rings. When masses of any considerable size were reached, probably exfoliation from the effects of rotation in the unscreened rays of the sun would give rise to flaking and thus prepare new matter for the milling process.

On the other hand, if magnetic particles were much developed, it is probable that their special attraction would aid in building up masses, so far as the supply of such material went. Probably such malleable substances as iron, nickel, and the other metals would weld rather freely by impact. Metallic particles might thus unite nearly to the extent they were permitted to come into collision. Such stony substances as brought crystalline or concretionary forces into play would probably build up more readily than other matter and more effectively resist destructive agencies afterward. But it must be noted in all these cases that as the molecules were more or less heterogeneously mixed originally, the opportunities for assembling homogeneous matter to form aggregates of any one kind would have natural limitations.

The logic of the case, taken all together, seems to lead to the conclusion that aggregates arising under these ideal planetesimal conditions would be limited to small sizes as a general rule. This is in harmony with the results realized in the Saturnian rings, and also in the zodiacal planetesimals to be more fully discussed in the next article. It is also in harmony with the dimensions attained by the chondri and chondrules that form characteristic constituents of 90 per cent of the stony meteorites. These range in size from a walnut down to spherules of dustlike minuteness.[2]

The point of most critical importance to our inquiry is the effect on selective action introduced by these growths so far as they went. In the first place, all such matter as continued in a free molecular state, whether aggregated as gases or deployed as planetesimals, would not be gathered about these small aggregates

[1] *Loc. cit.*

[2] O. C. Farrington, *Meteorites* (1915), p. 102.

by their own gravitative power. Incidentally molecules might be entrapped or occluded within these small bodies, or chemically united with them, or possibly even held against them by surface adhesion; but, otherwise, free molecules would rebound and escape control. Those solid particles that were highly elastic would also largely escape by rebound; those that were inelastic would more largely remain adherent after impact. Malleable substances like the metals would be likely to weld and cohere by collision. In general, these cohering bodies belong to the heavier order of substances, and so bodies formed in this way would be for the greater part selectively heavy.

If we could be sure that the chondrules of meteorites represent accretion of the foregoing type—a hypothesis to be seriously considered—it would give a specific insight into the cosmic aggregates of this order, for then they might be said to be dominantly formed of ferro-magnesian silicates, nickel-iron, and metallic sulphides, but it would be premature to draw this conclusion.

At any rate, since, on the one hand, these small bodies could not hold free molecules of the lighter order, and, on the other hand, the conditions were favorable for the aggregation of metallic substances, heavy silicates, sulphides, and so forth, it seems safe to conclude that *these small aggregates contained a relatively high proportion of inherently heavy matter.*

It seems to follow then that, if Mars, Venus, the earth, and the moon could have been gradually built up by the assemblage of particles, crystals, pellets, nodules, or even more considerable masses formed in this selective way, the percentage of heavier constituents could scarcely have been less in the earlier stages and in the smaller bodies than in the later stages and in the larger bodies, while they were probably somewhat distinctly greater; for in so far as these bodies succeeded in becoming large, they could then, but only then, have held the lighter order of molecules in a free state and thus have reduced their mean density. When atmospheres and hydrospheres were thus added, the processes of oxidation, hydration, and carbonation became important and the groundwork was laid for petrological derivatives from the products of these processes. A large class of the rocks and minerals of the outer

part of the earth, which usually have rather low specific gravities, are probably wholly dependent on the presence of the atmosphere and hydrosphere at the time of their formation. And so, if the moon, Mars, Venus, and the earth, could have been built up in this way, the moon should have the highest percentage of heavy material and the others should follow in the order of their masses, atmospheres, and hydrospheres. But it was previously shown that the conditions were very adverse to the building up of these four bodies in this way and there is no likelihood that they had such an origin.

It is perhaps worth while to add that, even if we were wrong in concluding that the planetesimal aggregates would be small, the result would be little different in density or in physical state, for as the aggregation of the particles in their orbits proceeded, the resulting aggregates would become more widely separated and further aggregation would take place only at correspondingly longer intervals. There would be little change in the kind of material or in the heat effects. The material would be a little more bunched before infall, but the bunches would be more scattered in space and successive infalls more distant in time. Precipitate aggregation is quite out of the question under these conditions.

As remarked at the beginning of this section, the material discharge from the rim of a rotating spheroid of gas by centrifugal action should form an ideal system of planetesimals, and so the method of their growth may be taken as a type of such action where the molecules are given subparallel orbits from the start and there is no commanding nucleus to gather them into bodies of the planetary order.

If this analysis is correct, it will be seen that the chance of developing a molten earth from a rotating gaseous nebula by centrifugal separation is about as remote as could well be imagined.

THE SELECTIVE SEGREGATION OF MATERIAL UNDER THE PLANETESIMAL HYPOTHESIS

The particular form of the planetesimal hypothesis which has been most fully worked out and tested postulates that the material of the planets was derived from the sun by means of its own

ejective activity stimulated to special intensity by the differential attraction of some passing body. Two essential factors are involved: (1) the ejection to the requisite distance of the requisite matter—only a fraction of 1 per cent of the sun's mass; and (2) the addition of sufficient transverse momentum to cause the ejected matter to revolve about the sun. The latter is the more critical factor, for the eruptivity of the sun is known to have such a high degree of efficiency, even at the present time, that only a relatively slight increase is required to project the small fraction of the sun's substance to the distance of the planets. Such projections would, however, fall back to the sun, unless they were given a transverse motion by some agency other than radial projection. A passing star or other body has been postulated to meet this requirement. The tidal stresses developed in the sun by such passing body would stimulate eruptivity and give direction to the projections while the pull of the passing body would draw the ejected matter into orbital courses.

In about a half-hundred cases worked out mathematically by Moulton to test the validity of the postulated effects, a star of medium size passing at from one to five astronomical units' distance was taken as the parent of the orbital motion; its diverting competency was found to be unexpectedly effective.[1]

Later it was suggested that a much smaller body—passing however much nearer to the sun—might serve as well to give both the tidal stimulus and the transverse motion required, but this has not yet been worked out mathematically.[2] Still more recent studies have led to the belief that there is a wide range of possibilities respecting the co-operating body, as will be specified later.

RECENT DISCLOSURES BEARING ON THE SOLAR PARENTAGE OF THE PLANETS

Respecting the projectile power of the sun, important light has been shed by very recent discoveries. Remarkable eruptions of the sun took place on May 29 and on July 15, 1919. A fine series of spectroheliographic photographs were taken at the Yerkes

[1] *Carnegie Year Book*, No. 5 (1906), pp. 166 and 168.

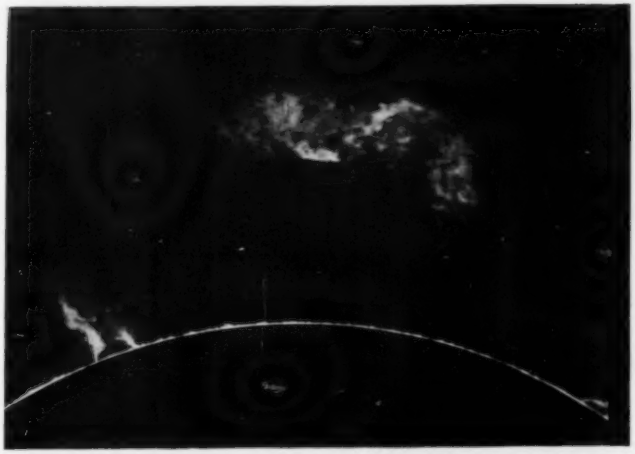
[2] *The Origin of the Earth* (1916), p. 118.

Observatory by Pettit and associates.[1] These disclose motions of quite an astonishing nature. Fortunately for our purposes, the photographs were taken with one of the calcium lines, and as calcium has the atomic weight 40 and enters widely into the constitution of the earth body, its projection in this effective way has more significance than if it were one of the lightest elements. The general facts of the two cases are shown by Plates I and II, reproduced here from Plates IV and VI of Pettit's article. Both eruptions gave rise to archlike forms. The apex of each arch vanished while it was still ascending, the first disappearing at a height of 760,000 km. above the surface of the sun, the second at 720,000 km., that is, at heights somewhat more than the radius of the sun in each case. At the time of disappearance the first had an ascensive velocity of 60 km. per sec., the second, 163.9 km. per sec. Perhaps the most remarkable features disclosed were suddenly increased rates of ascent taken on at intervals, while the rates of ascent between these stages of increase were essentially *uniform*. Thus in the eruption of May 29, there was a rise, for 50,000 km., from a point 150,000 km. above the surface of the sun at a rate of 5.5 km. per sec., when the rate changed to 9.2 km. per sec., which was maintained for 119,000 km., when the velocity again changed to 27.9 km. per sec., which was held for 91,000 km., when the rate again increased to 60 km. per sec., which was maintained for 230,000 km. and was still being held when the prominence vanished, doubtless either by cooling or dispersion or both. In the eruption of July 15, it was found that from 200,000 km. to 294,000 km. above the sun's surface the rate of ascent of the center of the arch was 37 km. per sec.; at the latter height the velocity abruptly increased to 163.9 km. per sec., which was held for no less than 426,000 km., and was still retained at the disappearance of the projected mass.

However these extraordinary phenomena are to be explained, two significant things are implied: (1) that in some way the gravitation of the sun is offset or neutralized sufficiently to permit uniform motion, so far at least as the projected matter was con-

[1] Edison Pettit, "The Great Eruptive Prominences of May 29 and July 15, 1919," *Astrophys. Jour.*, L (October, 1919), pp. 206–19.

c
G.M.T.
$5^h32^m41^s$



b
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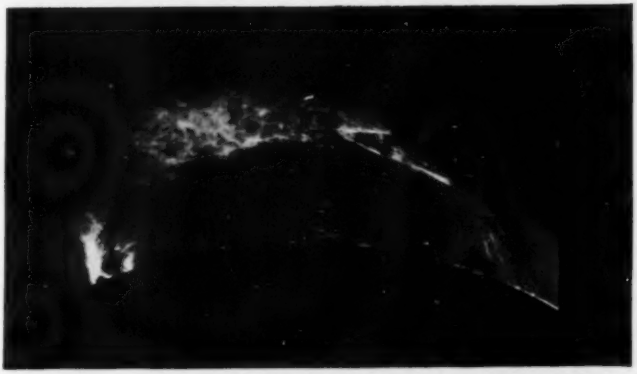
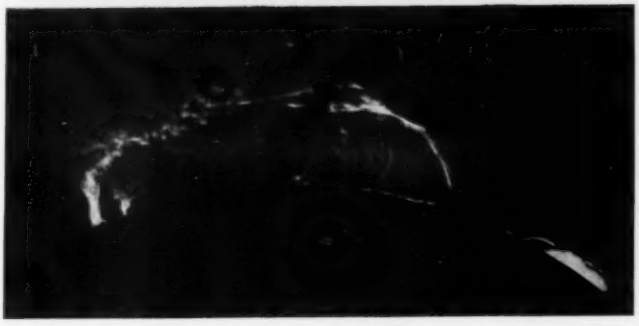
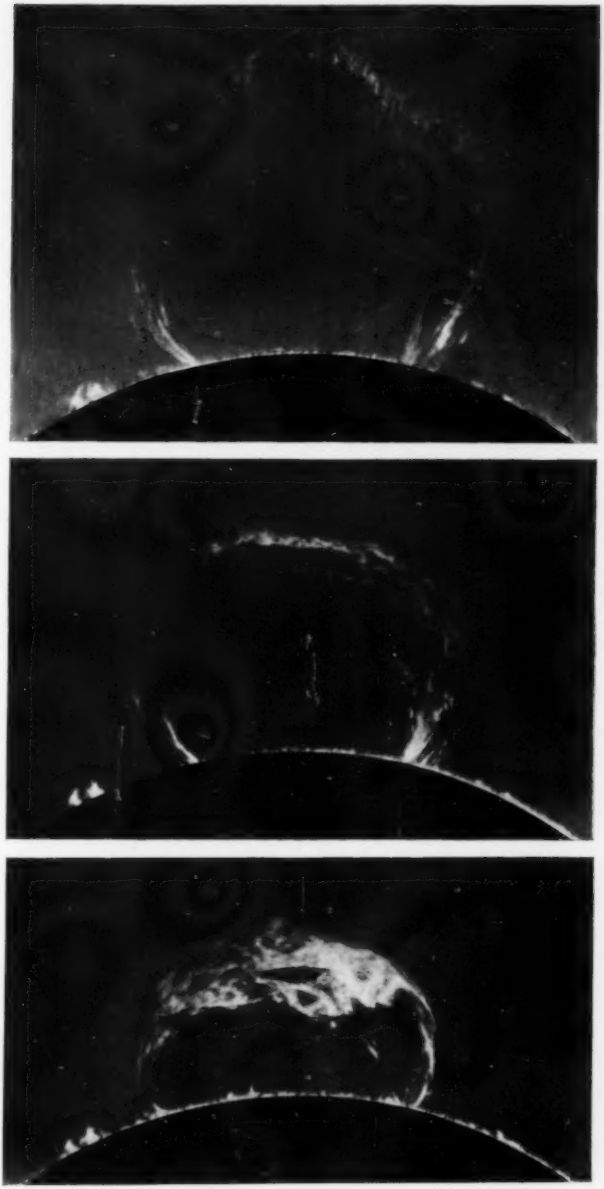


a
$1^h41^m16^s$



THE GREAT PROMINENCE OF MAY 29, 1919
Scale: for *a*, 1mm. = 9,326 km.; for *b* and *c*, 1 mm. = 8,416 km.
(After Pettit)



h
G.M.T.
$4^h 7^m 19^s$

g
$3^h 51^m 56^s$

f
$3^h 8^m 2^s$

THE PROMINENCE OF JULY 15, 1919
Scale: 1 mm. = 9,572 km.
(After Pettit)

cerned; and (2) that this matter received successive strong outward impulses, amounting in the last case to an increase of projection no less than 126.9 km. per sec. It is to be noted that this impulse was received after the arch had reached a height of 290,000 km. above the sun's surface. It is further to be observed that at the time the projections became invisible, in each case, more than half the restraining power of the sun, measured in terms of velocity, had been overcome. In the second case, the speed, at the time the projected matter became invisible, was competent to overcome more than half the remainder of the sun's restraining power.

Pettit finds data confirming these strange modes of movement, but of a less conclusive kind, in the photographs of certain other prominences already taken. He regards this singular mode of ascent by sudden accessions of speed with uniform motion between as the common one. However, none of these cases are sufficiently complete in themselves to show the full nature of these remarkable phenomena, for the ejected material passed out of sight while still under the highest observed uniform motion, and the extent to which this uniform motion may have continued and what followed it are left undetermined.

While further disclosures are required, and can only be awaited with eagerness, enough has already been revealed to give radical suggestiveness to these phenomena. They show that even at present and without obvious external stimulus there come into action, in addition to the internal eruptive forces, projectile forces of a high order which became effective at horizons high above the sun's surface, and that the combined projectile effect of these had overcome a large fraction of the restraining power of the sun before they passed out of sight.

Still another feature of the solar eruptions of May 29 and July 15, 1919, is scarcely less remarkable than their singular increments of motion. The projections on each of the two dates took the form of arches whose centers, at first low, rose impulsively into the forms shown on Plates I and II. The arch of May 29 was transverse to the sun's equator and had a chord of 584,000 km.; that of July 15 stood obliquely across the equator and had a chord of 363,000 km. as seen in perspective. The two ends of the arches appear

to have functioned quite differently. At one end, the arches seem to have sprung from short stumplike prominences that had been present for some time before the special eruptions of the dates named and remained for some time afterward. The movements of the calcium clouds near these seemingly originating ends were not only upward but inward toward the center of the arches. At the other end, the arches were apparently related to sun-spots. In these ends of the arches the calcium clouds seemed to be shooting swiftly toward the sun-spots. The photographs appear to show that special features in the upper part of the arches were drifting more or less from the prominence at the originating ends toward the sun-spot ends, though the motion of the central part of the arches was mainly upward. The total motions of the individual calcium molecules seem thus to have embraced a notable lateral component as well as the dominant ascensive one. The discovery by Hale and his associates that the cyclonic whirls associated with the sun-spots are negatively charged may perhaps be made to throw light on this. When ionization takes place by the discharge of an electrical element, it is usually the electron that is shot away, and the residual matter is then commonly positive. If, therefore, it be assumed that the calcium molecules shot forth from the stump prominences were positively charged, they would be drawn toward the negative charges of the sun-spot whirls.

A further feature of much interest is the suggestion of a rotational component in the projectile motion. This is implied in what has just been noted, a lateral movement combined with a vertical movement. A rather distinct expression of rotation seems to be shown in the spiraloid form of the upper central mass shown in Fig. *C*, Plate I. The value of this rotatory movement may be inferred from the fact that this spiraloid cloud had a volume more than 1,000 times that of the earth, assuming that its diameter in the line of vision was equal to the shorter of the two visible diameters.

While all these disclosures must remain *sub judice* until they have been amply verified and their interpretation made sure, it is permissible to bring their suggestiveness into service at once to mitigate the force of old views that always act as a drag upon new

views. These disclosures should help to lessen all hesitation in accepting the view that our atmosphere is even now receiving solar contributions. They should also lessen doubts as to the possibility of the projection of great masses of sun substance to planetary distances whenever stimulus is added to the spontaneous eruptivity of the sun.

MULTIPLE PHASES OF THE PLANETESIMAL HYPOTHESIS

In these new disclosures there is the germ of a new phase of the planetesimal hypothesis, a phase that may possibly dispense with aid from outside the solar system—heretofore supposed to be necessary—and so make the origin of planets a wholly domestic affair, though at present the suggestion does not look very promising. These disclosures seem to make the radial projection of the matter requisite for a planetary system possible without stimulus from outside. At the same time a *transverse* component of the projection is indicated in what has just been said about the lateral movement from the originating end of the arch toward the sun-spot end. If this lateral movement should prove adequate, and also be found to be preponderant in the right direction, it would contribute the component necessary to the revolution of the projected matter. The lateral movements in the two cases observed were chiefly across the equator of the sun, that is, normal to the required effect instead of coincident with it; but the position of the arches transverse to the line of sight in these two cases may be the essential reason why they were observed to such good effect. Similar movements in the line of sight, and in the direction of the sun's rotation, that is, the direction of planetary revolution, may not only be as common as these, but even be the predominant ones.

As the suggestion has only limited plausibility at present, it need not be further deployed here, but as it offers the possibility of a monoecious development of the planetary family in distinction from the dioecious origin heretofore postulated, even the shadow of such hypothesis is welcomed to a place among the multiple working sub-hypotheses that make up the planetesimal genus. Arranged with other developments of like order, the group of such sub-hypotheses embraces the following:

1. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter assigned to a passing star.*

a) Star of medium mass and distance (one to five astronomical units, more or less). Original type, tested mathematically by half-hundred concrete trial cases.

b) Giant star (in mass); distance great, tidal effect small, tangential effect large.

c) Diminutive star, distance relatively small, tidal effect relatively large, tangential effect relatively small.

2. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to some non-stellar body*, a stray planet for example. Approach to sun quite close, perhaps penetrating its Roche limit; tidal effect relatively great; adequacy of tangential effect less obvious, but assigned to the closeness with which the solar projections were shot out behind the passing body.

3. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to a special concentration of gravitative stress in open space arising from two or more related bodies of large mass*, for example, the center of gravity between two stars, or the concentrated gravity-stress of star clusters in certain forms of arrangement.

4. *Actuating forces arising wholly within the solar system.* Projectile effects assigned to eruptive and projective forces within the sun; the tangential effects assigned to co-operative action of positive and negative centers in the sun as suggested above. Little more than a suggested possibility.

CRITICAL PHASES OF THE EVOLUTIONARY PROCESS

Let us follow that form of the planetesimal hypothesis whose working competency has been most fully tested. According to this the nuclei of the planets and satellites arose from solar eruptions—those of the planets from the central masses of such eruptions, those of the satellites from subsidiary masses that closely accompanied these and kept within their spheres of control. It is our special task to follow the nuclei of the four little bodies under study from their source in the sun to their organized states, having especially in mind those features that bear on the segregation of

heavy from light material, but it will be helpful to keep in mind bodies of both the larger and the smaller orders. So far as the selection and the segregation of matter is concerned, there was no essential difference between the planets and the satellites as such, for each arose from independent portions of the erupted sun substance. The critical elements were the spheres of control dependent on mass and dynamic environment.

While we must await further light on the precise modes in which solar gas-masses are shot forth and the circumstances that induce them, we may be quite sure that, as they passed away from the sun into the outer field of its control, certain influences inevitably affected them. They must have been under the control of a projectile force sufficient to overcome the larger portion of the sun's total attraction. In this controlling force we may safely assume that there were conjoined (1) an original projectile force having its origin in the interior of the sun, (2) radiation pressure from the sun after the mass had left its surface, and (3) electrical effects, attractive and repellent, as also ballistic, that is, due to the momentum of electrons and alpha particles shot forth from the sun and caught by the escaping mass. Just what proportionate parts these co-operating agencies played in the total work of projection, we need not now inquire. It is taken for granted, since it is almost inevitable, that in escaping from the sun the gas-masses acquired some measure of rotatory motion, in addition to the rotation they already had as parts of the sun; there may have been included some measure of vortex motion as most eruptions generate such motion. There can be no question that practically all the constituents of the outbursts were in the gaseous state as they emerged from the sun and that they carried in to the subsequent evolution the molecular activities common to hot gases. The several projectile motions were more or less independently imposed on the emerging mass, and later these underwent more or less independent increases and declines, so that an important part of the ensuing evolution consisted in their mutual adjustment to one another. At the outset, the projectile velocity greatly preponderated over the velocities of all other motions, and until this became adjusted so as to be approximately proportionate to all

integers of the mass it was a prime source of turbulence and danger of dispersion. In so far as molecules were driven by it beyond the sphere of control of the common mass, they took courses of their own and, in the main, either returned by elliptical paths to the sun or became planetesimals. The danger of dispersion at this stage was a serious menace to all the minor masses whose self-control was feeble; at the same time it was a prolific source of planetesimal food for the growth of the nuclei later.

The hypothesis assumes that a part of the out-shot masses contained matter enough to give them self-control. The effectiveness of their control increased as they passed from the more intense to the less intense field of the sun's control, except as they lost material. But such self-control is not postulated of more than a part—probably less than half—the matter projected from the sun, the more scattered portion becoming planetesimals at once or else returning to the sun. Effective self-control is only assigned to a few of the greater eruptions, or, to be specific, to four of the major order, to form the nuclei of the four giant planets, and to four of the minor order, to form the nuclei of the terrestrial planets. But subordinate to these, perhaps a thousand or so little knots succeeded in holding themselves together and later grew into planetoids and satellites. It is thus assumed that there arose, as a result of eruptive projection and partial dispersion, a graded series of knots ranging from those that were massive enough to form the nuclei of the great planets down through medium and smaller knots to masses too small to hold themselves together in the face of the dissipating influences. It was of course in the lower ranges of this graded series that there arose the more critical questions of self-control and of permanent maintenance. The answers to these critical questions hung, in each individual case, very largely upon gravitative competency.

Now we need not dwell on the largest order of knots, for they do not enter our problem. Their strong attractions enabled them to hold their own, except for a small percentage of molecules that attained exceptional cumulative speeds, while, on the other hand, they were able to pick up stray planetesimals that came within their spheres of control in a favorable way. And so in the end,

between their ability to hold all sorts of molecules as well as pick them up, they came to have a much larger proportion of light molecules than the smaller bodies which could only hold the heavier ones, and so they now have relatively low specific gravities. Their great size helped them to remain hot, which also contributed to their low specific gravities. The largest of these is now more than three hundred times as massive as the largest of the terrestrial group; the mean mass of the giant planets is more than two hundred times the mean mass of the terrestrial planets. Our problem then is with a group of distinctly small bodies in which the balance between holding and non-holding power was more critical, and we need to enter somewhat more into detail.

1. As the material was shot forth from the sun, it was an intimate mixture of solar molecules of various kinds in a very hot gaseous form, and the molecules were interacting upon one another at speeds inversely proportional to the square roots of their molecular weights. In the process of forming definite knots under self-control out of the less-defined solar outbursts, of which a considerable part was dissipated into planetesimals or fell back to the sun, the lighter molecules of high speed would be more likely to be dissipated than the heavy ones of lesser speed, but we need not insist on that, as the dispersing danger came from the projectile force and probably was not very selective.

2. But when that contingency was passed and each knot began its own independent evolution, there arose a very definite selective process within the knot itself. We assume that for a short time the knots would still be hot and diffuse, and that during this stage there would be larger chances for molecules to escape from the control of the knot than later (*a*) because their velocities were highest on account of temperature, and (*b*) because their deployment was relatively open so that the molecules were less in one another's way when they happened to accumulate velocity enough to escape from control. We assume that this was the most crucial stage of the knot, and that selective loss was then its greatest danger. The lightest molecules, because they had the highest mean speeds and most frequently encountered and divided energies with other molecules, were those that most often acquired cumulative speeds

enough to enable them to escape. In each encounter there was an equi-partition of energy and the light molecules were given superior speeds in compensation for their lack of mass. The action was thus a highly selective process.

But lest we seem to overstress this depleting process, let it be noted that for every reaction that gave exceptional speed to a light molecule there was a reaction in a counter-direction that gave to the heavier partner in the encounter a lower velocity. And further, it was only in the outer border of the knot that the lighter molecule rebounding outward could usually find a way of escape without another collision and a rebound in the wrong direction, and so the effect of the counter-reaction was to drive a heavier molecule inward for every case in which a lighter molecule escaped. This tended to herd in the heavier molecules and make their mutual attraction more effective, while they were inherently more amenable to control. There was a loss of mass, to be sure, but there was a more than compensating loss of dissipating activity and the residue was more congenial to control.

Taking the knot as a whole, then, there was a steady progress toward a higher average of heavier molecules, and toward an assemblage more amenable to control. Those knots which had been given masses enough to endure this process soon reached a stage of safety and then began to build up by capturing such planetesimals as they could control. Those knots that could not endure the process dispersed into planetesimals or erratic wanderers. The hypothesis, of course, assumes that the nuclei of our four bodies had original masses enough to live through this critical stage, as did also those of all the planetoids and satellites, but it favors the belief that the smallest planetoids and satellites represent the lower limit of successful knots, for if still smaller ones were successful we might expect to see their representatives in the heavens about us. The giant hot stars are, of course, the greatest known examples of success in holding light, hot gases by self-gravity. The multitude of these are our assurance that the principle of gaseous self-control is sound and that it has realization of the highest order in the great cosmos.

It scarcely need be added that the severest selection of heavy molecules would be realized in the smallest knots where the struggle to maintain themselves was most strenuous, and that in the intermediate class the percentage of heavy molecules would be inversely proportional to mass.

All this relates to the purely molecular state assumed to prevail while the knots were organizing themselves out of solar ejections and were beginning their careers as the nuclei of growth into mature planets, planetoids and satellites.

3. Let us turn now to the inner evolution of these nuclei. Let us recall that immediately on the emergence of the gas-masses from the sun there was great expansion and much cooling in consequence. Rapid radiation must have followed as the expanded mass shot out into the relatively cold space of the outer regions. It seems inevitable therefore that the condensation temperatures of the refractory material that now makes up most of the solid body of the earth, and doubtless of its neighbors, would be reached at a succession of stages relatively early in the history of the medium and smaller order of knots. We may assume that the condensation into minute spherules was started by electric charges and followed essentially the lines already sketched in the study of the derivatives from a rotating spheroidal nebula. There was this difference, however. The centrifugal derivatives from the rotating nebula were planetesimals each following its own orbit. The condensations within the nuclei were, at first at least, scattered through the uncondensed portion that was still gaseous. The condensed spherules or crystals were like cloud particles or dust particles in an atmosphere. Dynamically they were like Brownian particles, jostled about by the impacts of the molecules that still remained in the gaseous state. They would naturally develop earliest in the outer parts of the nuclei and later in the inner parts. They would constitute a class of bodies heavier than the molecules and would tend to damp molecular action, while they themselves would tend to fall toward the center of the nuclei, but their fall would be resisted by the part that remained gaseous. It is obvious that the condensation of the refractory heavy material into spherules or

crystals in the midst of the gaseous molecules would mark the turn of the tide in the history of the smaller nuclei for the molecular losses would speedily grow less and a definite centralizing movement would set in which would increase the power of self-control. Molecular losses would be lessened and the capture of planetesimals increased relatively.

The question of the temperatures and the physical states that would follow this stage in the smaller nuclei is important and difficult but must be deferred.

4. It remains only to consider the selective action of the successful nuclei in the process of gathering in planetesimals, but this need not detain us for the principles would be essentially those already emphasized sufficiently. The smaller order of nuclei could not capture and hold the lighter free molecules as such, though they could perhaps capture and retain the very heavy molecules. They could quite certainly hold most of the planetesimal aggregates that they encountered but would have little power to draw them to themselves. The nuclei of medium mass could hold some of the free molecules but not the lightest, and so their accessions would be greater in mass, but lower in mean specific gravity.

SUMMARY

It seems clear, then, from the foregoing considerations that, *in general, the planets, planetoids, and satellites, if built up by the planetesimal method, would be composed of inherently heavy material in inverse proportion to their masses*, and hence that the inherent specific gravity of the matter of the moon would be somewhat greater than that of Mars, that of Mars somewhat greater than that of Venus, and that of Venus greater than that of the earth.

There is still need to consider (1) what were the physical states of the nuclei while they were gathering in the planetesimals, (2) what masses the planetesimals attained, and (3) what was the effect of their infall on the later stages of the growing bodies. This last will obviously involve the frequency of the fall of the planetesimals upon the nuclei. The discussion of these points must be deferred to the next article.

It may be noted, however, that the physical state of the matter, whatever it may be, will not radically affect the mean constitution of the bodies, though it is liable to affect greatly the distribution of the material. Reserving judgment on any shrinkage effect that may arise from such difference of distribution, we may note that the inquiries of this paper, in harmony with the suggestions of the previous paper, very distinctly imply that, if the moon, Mars, Venus, and the earth were built up normally by the planetesimal method, they should contain proportions of inherently heavy material in the inverse order of mass. There is therefore corresponding reason to think that the estimate of the total shrinkage of the earth deduced in the preceding article will need to be somewhat increased, as anticipated, on account of the differences of material that make up the four bodies compared.

A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS—REVISED

ALBERT JOHANNSEN
University of Chicago

PART II

CLASS 2, ORDER 1

(210) **Meso-**silexite. See note under (110).

(211) **Moyite.** The rocks of this family are quartz-orthogranites. Since three of the rocks described by Daly[1] from the Moyie sill along the Forty-ninth Parallel are of this uncommon type, the term moyite is here suggested for the family name.

(215) Rockallite JUDD. The name rockallite is derived from the Island of Rockall, off the coast of Ireland. Judd[2] describes the rock as composed of aegirite, quartz, and albite. While the presence of aegirite makes the rock abnormal, the term may be used, at least temporarily, for the family name. Rockallite is a quartz-rich aegirite-albite-tonalite.

(216) **Ortho**granite. This is a comparatively rare rock, only differing from normal granite in containing no plagioclase. In this group also belong anorthoclase-granite, potash-rhyolite (**ortho**rhyolite), comendite, and some grorudites and solvsbergites. Many of the granites belonging here are aegirite- or riebeckite-bearing. For the use of the prefix "ortho-" see (111).

Microcline-granite.
Anorthoclase-granite.
Orthogranitite.

[1] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Canada, Mem. 38*, Part I, pp. 229, 230, 231.

[2] J. W. Judd, "On the Petrology of Rockall," *Trans. Royal Irish Acad. Dublin*, XXI (1897), 49–57.

Orthorhyolite is the extrusive equivalent of this family.

Comendite BERTOLIO[1] is an aegirite-rhyolite.

Paisanite OSANN. Paisanite was named from Paisano Pass, Texas, by Osann.[2] It is a dike rock composed of quartz, microperthite, and riebeckite.

(217) Albite-granite. The term albite-granite is here applied to a normal granite containing orthoclase and plagioclase between the proportions 95:5 and 65:35. The plagioclase, however, is albite, and not the usual oligoclase. A new name should be chosen, since the terms soda-granite, albite-granite, albite-syenite, etc., have been used for rocks with albite as the only feldspar, that is, for rocks which properly are called albite-tonalite, albite-diorite, etc., in this classification.

Albite-rhyolite. The extrusive equivalent of the preceding. The objection to the term albite-granite applies also to albite-rhyolite.

(218) **Albite**-adamellite. No confusion can result from the use of this term, since adamellite conveys the idea of a quartz-monzonitic rock, and the prefix indicates that the plagioclase of the orthoclase-plagioclase combination is albite. A number of grorudites fall here, as does also a lindoite, and numerous arfvedsonite- and riebeckite-granites, so called.

Albite-dellenite. The extrusive of the preceding.

(219) **Albite**-granodiorite. There is no possibility of misunderstanding this name. See notes under (218) and (229).

Albite-rhyodacite. See note under (229).

(2110) **Albite**-tonalite. The meaning of this term also is unmistakable. See note under (217). For the use of tonalite for quartz-diorite see (2210).

Albite-dacite. The extrusive of preceding.

[1] S. Bertolio, "Sulle comenditi, nuovo gruppo di rioliti con aegirina," *Atti. della Reale Accad. dei Lincei, Cl. scienze fisiche, mat. e nat.*, IV (1895), 2 semestre, pp. 49–50.

[2] A. Osann, "Report on the Rocks of Trans-Pecos, Texas," *4th Ann. Rept. Geol. Surv. Texas* (1892), p. 132.

(2111) **Ortho**syenite. This family includes syenites with orthoclase, microcline, microperthite, or anorthoclase, but with less than 5 per cent plagioclase.

Orthotrachyte. The extrusive equivalent of the preceding.

(2112) Albite-syenite. A term less likely to be misunderstood should be chosen for this family. See note under (217).

Albite-trachyte. See note under (217).

(2113) **Albite-**monzonite. This term cannot be misunderstood. See note under (218).

Albite-latite. The extrusive equivalent of the preceding.

(2114) **Albite-monzodiorite.** See note under (218). For the use of monzodiorite see (2214).

Albite-andelatite. The extrusive equivalent of the preceding. See note under (2214).

(2115) **Albite-**diorite. This term also is unmistakable. The word diorite conveys the impression of a plagioclase rock, and the prefix suggests that this feldspar is albite. The term soda-syenite has been used for this rock, but it was badly chosen. Soda-syenite naturally suggests a syenite rich in soda feldspar, but not to the exclusion of orthoclase. Albite-diorite is a much better term.

Albite-andesite. The extrusive equivalent of the preceding.

(2116) Pulaskite WILLIAMS. This term is used in the sense of Williams'[1] original definition: "a rock made up of orthoclase, pyroxene, amphibole, and *a little* eleolite or its decomposition product, analcite." In another place[2] he says that the orthoclase is "similar to Brögger's kryptoperthite, although the amount of soda is somewhat less than is usually found in this." The rock, therefore, clearly falls into (2116), for while the dark constituents are not prominent they are greater than 5 per cent, as was shown by the examination of various thin sections from the type locality. Brögger's[3] type laurvikite belongs here, but the

[1] J. Francis Williams, "The Igneous Rocks of Arkansas," *Ann. Rept. Geol. Surv. Arkansas for 1890*, II, 20.

[2] *Ibid.*, p. 60.

[3] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits* (Kristiania, 1898), p. 30.

characteristic texture of this rock excludes it from representing the family.

(2121) **Ortho**-nephelite-syenite, **ortho**-leucite-syenite. This is nephelite- (or leucite-) syenite without plagioclase.

Orthofoyaite. See note under (2222).

Orthoditroite. See note under (2222).

Orthophonolite. The extrusive equivalent of the preceding.

(2122) **Albite**-nephelite-syenite, **albite**-leucite-syenite. Nephelite-(leucite-) syenites carry orthoclase either as the only feldspar or in combination with plagioclase, which may be albite or some other member of the series. In this family (2122) belong those carrying albite.

Albite-foyaite. See note under (2222).

Albite-ditroite. See note under (2222).

Albite-phonolite. The extrusive corresponding to the preceding.

(2123) **Albite**-nephelite-monzonite. Here belong numerous tinguaites and so-called nephelite-syenites, also a sodalite-foyaite and a cancrinite-syenite. Covite WASHINGTON, according to the calculated mode, belongs here, but under the definition Washington[1] says the rock is a "leucocratic combination of orthoclase and less nephelite with hornblende and aegirite-augite," which would place it in Family 21.

(2124) Litchfieldite BAYLEY. In his description of litchfieldite Bayley[2] says: "As was indicated by the microscopic study, no plagioclase other than albite is present, and this, as seen (from a calculated mode), is largely in excess of the orthoclase." The mode computed from the analysis indicates 27 per cent orthoclase and microcline, 47 per cent albite, 17 per cent nephelite, and 2 per cent cancrinite. These proportions are about the same as shown by the thin section and Thoulet separation. While cancrinite occurs in the type rock, Bayley[3] says: "I do not regard

[1] Henry S. Washington, "The Foyaite-Ijolite Series of Magnet Cove: A Chemical Study of Differentiation," *Jour. Geol.*, IX (1901), 615.

[2] W. S. Bayley, "Eleolite-Syenite of Litchfield, Maine," *Bull. Geol. Soc. Amer.*, III (1892), 242.

[3] *Ibid.*, *In litteris*, June 14, 1919.

cancrinite as an essential constituent . . . . and many of the specimens show none. . . . . Some of it is certainly secondary." The rocks of this family may therefore be divided into

Litchfieldite (normal).

Cancrinite-litchfieldite.

The calculated mode of canadite QUENSEL[1] places it in this family, but the actual mineral composition may be quite different. Quensel[2] says that "a rock entirely consisting of nephelite, albite, and a mafic mineral may or may not be a canadite, depending upon the presence or absence of a certain amount of normative lime-feldspar." Depending thus upon chemical composition for its name, it is excluded here.

(2125) Mariupolite MOROZEWICZ. Morozewicz[3] described certain rocks from the shores of the Sea of Azof which consist of much albite, less nephelite, and some ferromagnesian constituents and zircon. He gives two modal analyses, determined microscopically, both of which fall in this family somewhat above the center point.

(2126) Naujaite USSING. Several nephelite- and leucite-syenites belong here, as does also arkite WASHINGTON.[4] The latter, however, is too poor in feldspar to be typical of the family, and it carries garnet as an essential. Naujaite USSING[5] is the rock originally described by Steenstrup[6] as a sodalite-syenite. Pending the location of a nephelite-rich orthofoyaite or orthoditroite, naujaite may represent the family.

Syn.: Sodalite-syenite STEENSTRUP.

Arkite WASHINGTON.

[1] Percy Quensel, "The Alkaline Rocks of Almunge," *Bull. Geol. Inst. Upsala*, XII (1914), 135, 176–77.

[2] *In litteris*, May 16, 1915.

[3] J. Morozewicz, "Über Mariupolit, ein extremes Glied der Eleolithsyenite," *Tscherm. Min. Petr. Mitth.*, XXI (1902), 245.

[4] Henry S. Washington, "The Foyaite-Ijolite Series of Magnet Cove: A Chemical Study in Differentiation," *Jour. Geol.*, IX (1901), 617.

[5] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Meddel. om Grönl.*, XXXVIII (1911), 32, 143–56.

[6] K. J. V. Steenstrup, "Bemaerkninger til et geognostisk Oversigtskaart over en Del af Julianehaabs Distrikt (den 20 Juni 1878)," *Meddel. om Grönl.*, II (1881), 35.

(2127) **Beloeilite.** O'Neill[1] described a "feldspathic tawite" from Mount St. Hilaire (Beloeil), Quebec, intermediate in composition between sodalite-syenite and tawite. This rock may be called beloeilite and may serve as the type of the sodalite rocks of the family.

(2129) A soda-sussexite of Hackman[2] and a nephelite-sodalite-syenite of O'Neill[3] belong here.

(2130) **Toryhillite.** Adams and Barlow[4] described a nepheliterich albite rock from Toryhill, Monmouth Township, Ontario. The rock falls near the center point of this family; therefore a new name is here suggested.

(2131) Urtite RAMSAY. Urtite is a feldspar-free nephelite rock, described by Ramsay.[5] The name is derived from the second part of Lujavr-Urt, where the rock was first found. It consists of 82 to 86 per cent nephelite, 12 to 18 per cent aegirite-augite, and 2 per cent apatite. Ijolite RAMSAY and BERGHELL,[6] with 51.6 per cent nephelite, and monmouthite ADAMS and BARLOW,[7] with 77.6 per cent feldspathoid (of which 72 is nephelite), also belong here. The leucite rock of this family is fergusite PIRSSON.[8] Only a single occurrence is known. It consists of 65 per cent pseudoleucite and 35 per cent mafites, chiefly diopside. The melilite rock of the family is represented by uncompahgrite LARSEN.[9] It is a

[1] J. J. O'Neill, "St. Hilaire (Beloeil) and Rougemont Mountains, Quebec," *Geol. Surv. Canada, Mem. 43* (Ottawa, 1914), p. 46.

[2] V. Hackman, "Neue Mitteilungen über das Ijolithmassiv in Kuusamo," *Bull. d. l. Comm. Geol. d. Finlande*, No. 11 (Helsingfors, 1899), p. 24.

[3] J. J. O'Neill, *op. cit.*, p. 41.

[4] Frank D. Adams and Alfred E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Geol. Surv. Canada, Mem. 6* (1910), p. 273.

[5] Wilhelm Ramsay, "Urtit, ein basisches Endglied der Augit-syenit-Nephelinsyenit-Serie," *Geol. Fören. i. Stockh. Förhandl.*, XVIII (1896), 463.

[6] Wilhelm Ramsay and Hugo Berghell, "Das Gestein vom Iiwaara in Finland," *Geol. Fören. i. Stockh. Förhandl.*, XIII (1891), 304; also V. Hackman, *op. cit., supra*, p. 20.

[7] Frank D. Adams and Alfred E. Barlow, *op. cit.*, p. 277.

[8] Louis Valentine Pirsson, "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," *U.S. Geol. Surv., Bull. 237* (1905), p. 88.

[9] Esper S. Larsen, "Melilite and Other Minerals from Gunnison County, Colorado," *Jour. Wash. Acad. Sci.*, IV (1914), 473.

deep-seated rock consisting of two-thirds melilite and one-third dark constituents (magnetite and pyroxene) with some accessory perofskite and apatite. The extrusive equivalent is melilite-basalt STELZNER[1] (Syn. Melilithit LOEWINSON-LESSING[2]).

CLASS 2, ORDER 2

(222) **Quartz**-granite. Since the term granite in itself carries the idea of a quartz-bearing rock, the term quartz-granite will indicate a granite that is rich in quartz. All other rocks which, by definition, carry quartz may be similarly qualified, namely, adamellite, granodiorite, tonalite, etc.

(223) **Quartz**-adamellite. See note under (222). Here belongs, though far from the center point, the Hauksuo, Kisko, aplite, described by Eskola,[3] which consists of quartz 48.9 per cent, plagioclase (average $Ab_{85}An_{15}$) 22.9 per cent, microcline 20.4 per cent, biotite 4.4 per cent, magnetite 1.9 per cent, and epidote 1.5 per cent.

(224) **Quartz**-granodiorite. See note under (222).

(225) **Quartz**-tonalite. See note under (222). For the use of tonalite for quartz-diorite see (2210).

(227) Granite. This term is of very old date. It is not found in Pliny. Breislak says it was first used by Caesalpinus[4] in 1596. The name may be derived from the Italian *granito*, "grained" (Lat. *granum*), but its origin is uncertain. The word is similar in sound in many languages, for example, *gwenith faen* ("wheat stone") in Welsh, and it is possible that the name was brought from Wales by the Romans who built roads and worked the mines there about 78 A.D.

Family (227) is that of the normal granites. These rocks consist of quartz, orthoclase, less oligoclase or andesine, and a moderate

[1] Alfred Stelzner, "Mittheilungen an den Redaction," *Neues Jahrb.*, I (1882), 230–31; also "Über Melilith und Melilithbasalte," *Neues Jahrb., B.B.*, II (1882), 364–440.

[2] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, IV," *T.M.P.M.*, XX (1901), 114.

[3] Pentti Eskola, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. d. l. com. géol. d. Finlande*, No. 40 (1914), p. 83.

[4] Andreas Caesalpinus (Cesalpino), *De Metallicis* (1596), II, cap. 11.

amount of mafic minerals. There are many subfamilies, depending upon the accessories or dark constituents.

Granitite. This is an old term which has been used with a great variety of meanings. So long ago as 1823 von Leonhard[1] said that the proposal to call granites with accessory minerals granitite was superfluous and unfitting. Rose[2] used the word for muscovite-free biotite-bearing rocks with quartz, orthoclase, and considerable oligoclase. It was used in the same sense by Senft[3] and Rosenbusch,[4] and is here also used as a synonym for biotite-granite. Cathrein's[5] suggestion that it be used for plagioclase-rich hornblende-bearing granites has never been followed.

Amphibole-granite.

Arfvedsonite-granite BRÖGGER.[6]

Augite-granite.

Binary-granite KEYES[7] contains both muscovite and biotite. It is also called two-mica granite.

Hypersthene-granite.

Syn.: Charnockite HOLLAND.[8]

Microcline-granite.

Muscovite-granite.

Tourmaline-granite, etc.

Rhyolite VON RICHTHOFEN. The name rhyolite (from ῥύαξ, "lava stream," "torrent") was given by von Richthofen[9] to the extrusive equivalent of granite on account of its usual fluidal

[1] K. C. von Leonhard, *Charakteristik der Felsarten* (Heidelberg, 1823), I, 54.

[2] Gustav Rose, "Ueber die zur Granitgruppe gehörenden Gebirgsarten," *Zeitschr. d. d. geol. Ges.*, I (1849), 386; also pp. 363–66.

[3] Ferdinand Senft, *Classification und Beschreibung der Felsarten* (Breslau, 1857), p. 297.

[4] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (1st ed.; Stuttgart, 1877), II, 20–21.

[5] A. Cathrein, "Zur Dünnschliffsammlung der Tiroler Eruptivgesteine," *Neues Jahrb.*, I (1890), 72.

[6] W. C. Brögger, "Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite," *Zeit. f. Kryst.*, XVI (1890), 68.

[7] Charles Rollin Keyes, "Origin and Relations of Central Maryland Granites," *U.S. Geol. Surv., Ann. Rept.*, XV (1895), 714.

[8] T. H. Holland, "The Charnockite Series, a Group of Archean Hypersthenic Rocks in Peninsular India," *Mem. Geol. Surv. India*, XXVII (1900), 2, 119.

[9] Ferdinand Freiherrn v. Richthofen, "Studien aus den ungarisch-siebenbürgerischen Trachytgebirgen," *Jahrb. d. k. k. geol. Reichsanst.*, XI (1860), 156.

character. Roth[1] called the same rocks liparites, from the Lipari Islands, where they occur.

Syn.: Liparite ROTH.

Nevadite VON RICHTHOFEN. Nevadite is a variety of rhyolite with very abundant phenocrysts and very little groundmass. It was named by von Richthofen[2] from its occurrence in Nevada.

(228) Adamellite CATHREIN-BRÖGGER. The term adamellite is here given to quartz-monzonites. It was originally used by Cathrein[3] for rocks from Adamello which contain both orthoclase and plagioclase. Speaking of these rocks he says: "Er ist ein lichtes, schon im Aussehen mehr den Graniten als Dioriten sich näherndes Gestein." Brögger[4] uses the name for acid quartz-monzonites, and Ball[5] and Hatch[6] use it for quartz-monzonite.

Syn.: Quartz-monzonite BRÖGGER.

Windsorite DALY.[7] This is a quartz-poor quartz-monzonite dike-rock.

Dellenite BRÖGGER. The rock intermediate between dacite and rhyolite from Dellen, Helsingland, Sweden, was named dellenite by Brögger,[8] and the term is here used for the extrusive equivalent of quartz-monzonite. Since it consists of a single word it is preferable to quartz-latite.

Syn.: Quartz-latite RANSOME,[9] Dacite-liparite BRÖGGER.[10]

[1] Justus Roth, *Gesteinsanalysen*, xxxiv (1861).

[2] F. Baron von Richthofen, "Principles of the Natural System of Volcanic Rocks," *Mem. Cal. Acad. Sci.*, I (1868), Part II, p. 16.

[3] A. Cathrein, "Zur Dünnschliffsammlung der Tiroler Eruptivgesteine," *Neues Jahrb.*, I (1890), 74.

[4] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 61.

[5] Sydney H. Ball, "General Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Wash., Prof. Paper 63* (1908), p. 51.

[6] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), p. 176.

[7] R. A. Daly, "The Geology of Ascutney Mountain, Vermont," *U.S. Geol. Surv., Bull. 209* (1903), p. 46.

[8] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 59, note.

[9] F. Leslie Ransome, "Some Lava Flows of the Western Slope of the Sierra Nevada, California," *Amer. Jour. Sci.*, V (1898), 372.

[10] W. C. Brögger, *op. cit.*, p. 60.

(229) Granodiorite BECKER. The term granodiorite was suggested by Becker[1] for plutonic rocks containing both orthoclase and acid plagioclase, the latter in excess of the former. The name was first published in a paper by Lindgren[2] in 1893 and described in more detail later.[3] Lindgren[4] says: "The truly characteristic feature of the granodiorites is that the soda-lime feldspar, which always is a calcareous oligoclase or an andesine, is *at least* equal to double the amount of the alkali feldspar. The latter may be taken to vary from 8 per cent to 20 per cent" in a rock with an assumed feldspar content of 60 per cent.[5] "Below the lower limit the rock becomes a quartz-diorite: above the upper a quartz-monzonite." "In the quartz-monzonite," he continues, "I would give this mineral a range from 20 per cent to 40 per cent," again assuming a total of 60 per cent feldspar. His divisions, therefore, based on the orthoclase-plagioclase ratio are $0–13\frac{1}{3}–33\frac{1}{3}–66\frac{2}{3}$ for quartz-diorite, granodiorite, and quartz-monzonite. In the present classification the divisions are taken at 0–5–35–65, the writer believing that more than 5 per cent of orthoclase changes the character of a quartz-diorite too much for it to retain that name. Setting apart as orthogranite the rock with 95 to 100 per cent of its feldspar orthoclase, and as quartz-diorite that having 95–100 per cent plagioclase, the remaining 90 parts are divided into three

[1] Waldemar Lindgren, "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 270.

[2] *Ibid.*, "The Auriferous Veins of Meadow Lake, California," *Amer. Jour. Sci.*, XLIV (1893), 202.

[3] *Sacramento Folio, U.S. Geol. Surv.*, No. 5, 1894; *Placerville Folio*, No. 3, 1894; *Smartsville Folio*, No. 18, 1895; *Nevada City Folio*, No. 29, 1896; *Pyramid Peak Folio*, No. 31, 1896; *Truckee Folio*, No. 39, 1897; H. W. Turner, "The Rocks of the Sierra Nevada," *U.S. Geol. Surv.*, An. 14, pp. 478, 482; Waldemar Lindgren, "The Gold-Silver Veins of Ophir, California," An. 14, *U.S. Geol. Surv.*, Part II (1894), pp. 252, 255–56; also "The Gold Quartz Veins of Nevada City and Grass Valley Districts, California," An. 17, *U.S. Geol. Surv.*, Part II (1896), p. 35; "The Granitic Rocks of the Pyramid Peak District, Sierra Nevada, California," *Amer. Jour. Sci.*, III (1897), 308; "The Granitic Rocks of Sierra Nevada," *Abstr. in Science*, New Series, V (1897), 361; "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 269–82.

[4] Waldemar Lindgren, "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 277.

[5] *Ibid.*, p. 279.

equal portions, one each for normal granite, quartz-monzonite, and granodiorite.

The term granodiorite is not the most satisfactory, from the standpoint of the construction of the word, for a rock intermediate between quartz-monzonite (adamellite) and quartz-diorite (tonalite), for it suggests a rock intermediate between a granite (an orthoclase-quartz-bearing rock) and a diorite (a plagioclase-quartz-free rock), that is, a quartz-monzonite. Monzonite in the sense in which we now use it, however, was not introduced by Brögger until 1895, while granodiorite was first used in 1892 or 1893. The term was intended to convey the idea of a diorite with granitic characters, that is, with quartz and a certain amount of orthoclase, but upon the introduction of the term monzonite Lindgren[1] found it advisable to restrict the "definition of granodiorite to rocks considerably nearer quartz-diorite than originally intended." A name derived from the rocks between which granodiorite, as now defined, actually stands would give adam-tonalite, which is hardly euphonious, to say the least. Furthermore, the term granodiorite is so firmly established and was so clearly defined that it should not be changed.

The term banatite was used by Brögger[2] for his intermediate quartz-monzonites, and under this term are included rocks which are probably to be classed as quartz-poor granodiorites (see under 2213).

The objection to the construction of the word granodiorite as applied to rocks under the present definition applies also to the terms introduced by the present writer[3] in 1917, namely granogabbro, syenodiorite, and syenogabbro. But since granodiorite is retained for the reasons stated above, and adam-gabbro is as objectionable as adam-diorite, granogabbro (239) also will be retained to make analogous terms. The names of the extrusive rocks should naturally conform in construction to their deep-seated equivalents; consequently rhyodacite WINCHELL is used for the

[1] Waldemar Lindgren, *In litteris*, June 17, 1919.

[2] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 60.

[3] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), p. 89.

granodioritic extrusive, and rhyobasalt is here proposed for the granogabbroic. Syenodiorite and syenogabbro will be replaced by the better terms monzodiorite and monzogabbro. For the corresponding extrusives, ande-latite and basa-latite are here proposed.

Rhyodacite WINCHELL.[1] See note under granodiorite above. This is the extrusive equivalent of granodiorite.

(2210) Tonalite VOM RATH-BRÖGGER-SPURR. Tonalite was applied by vom Rath[2] to a certain rock from Monte Tonale, in the Tyrol. It consists of abundant quartz, andesine, very small amounts of orthoclase as an accessory, and a dark mineral. In the definition, however, vom Rath omitted the orthoclase, which occurs as micropegmatite and was regarded simply as an accessory, and said: "Der Tonalit enthält in körnigem Gemenge als wesentliche Bestandtheile: eine trikline Feldspath-Species, Quarz, Magnesiaglimmer und Hornblende." In his tabulation Brögger[3] used tonalite for acid quartz-diorite, and in another place[4] he said: "Der Name Tonalit wäre dann den Quarzdioriten vorbehalten." Since Brögger does not use the subdivision granodiorite, his tonalite includes some of these rocks. Simply as quartz-diorite the term was used by Spurr,[5] who adopted it as a group name instead of quartz-diorite, because it "is shorter and more characterizing." In the same sense it was used by Winchell[6] and Hatch,[7] and it is so used here.

Incidentally, the average igneous rock of Clarke,[8] computed into common minerals, falls in this family. It contains quartz

[1] Alexander N. Winchell, "Rock Classification on Three Co-ordinates," *Jour. Geol.*, XXI (1913), 214.

[2] G. vom Rath, "Beiträge zur Kenntniss der eruptiven Gesteine der Alpen," *Zeitschr. d. d. geol. Ges.*, XVI (1864), 250.

W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 60.

[4] *Ibid.*, p. 61.

[5] J. E. Spurr, "Reconnaissance in Southwestern Alaska in 1898," *U.S. Geol. Surv., Ann. Rept.*, XX, Part VII (1900), p. 190.

[6] Alexander N. Winchell, "Rock Classification on Three Co-ordinates," *Jour. Geol.*, XXI (1913), 214.

[7] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), p. 195.

[8] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv., Bull. 491* (1911), p. 31.

12 per cent, andesine 59.2 per cent, pyribole 16.8 per cent, mica 3.8 per cent, and other accessories 7.9 per cent.

Syn.: Quartz-diorite.

Dacite STACHE. The name dacite was given by Stache[1] to certain older quartz-trachytes, found in Siebenbürgen (Dacia), which contain oligoclase and pyroxene and which were thus thought to be separated from the younger quartz-trachytes or rhyolites which contain sanidine and biotite. The term has been variously used by different petrographers, some applying it only to extrusive plagioclase rocks with quartz phenocrysts, others including rocks whose only quartz is in the groundmass; some requiring the presence of pyroxene, others including rocks with biotite. In general the name has come to mean quartz-andesite, the extrusive equivalent of quartz-diorite, and it is so used here.

Syn.: Quartz-andesite.

(2212) Syenite. The name syenite was used at least as long ago as the time of Pliny,[2] and was apparently in common use in his day for the rocks from Syene (Assuan), Egypt. "Circa Syenen vero Thebaidis Syenites," he says, "que ante pyrrhopoecilon vocabant," that is, spotted with red. Werner[3] applied the term Sienit to the hornblende-bearing rock from near Dresden, under the impression that the two were the same. It was later found that the Syene rock contains quartz, is, in fact, hornblende-granite, while the Dresden rock is practically quartz-free. Some writers consequently used the term syenite for hornblende-granite, but generally it was used for quartz-free orthoclase rocks in the sense of Werner. Rosière[4] found that the rock of Mount Sinai is of the quartz-free variety and therefore proposed that the name be changed to sinaite. The older term, however, was in such common use that this suggestion was not followed.

[1] G. Stache, "Quarztrachyte Siebenbürgens," in Fr. von Hauer and G. Stache, *Geologie Siebenbürgens* (1863), pp. 56, 70, 79.

[2] C. Plinii Secundi *Naturalis historiae* xxxvi. cap. viii. In the edition Lugd. Batav. Roterodami, Ao. 1668, p. 647.

[3] "Vermischten Nachrichten," *Bergmännisches Journal*, II (1788), 824.

[4] J. F. d'Aubuisson de Voisins, *Traité de géognosie* (Strasbourg et Paris, 1819), p. 21.

There are many varieties of syenite, depending upon the character of the dark or accessory constituents.

Biotite syenite.

Syn.: Syenitite LOEWINSON-LESSING,[1] analogous to granitite for biotite-granite. Polenov,[2] however, had previously used the term in a different sense, namely for syenite-aplite.

Hornblende-syenite.

Arfvedsonite-syenite.

Augite-syenite.

Epidote-syenite.

Pyroxene-syenite.

Hypersthene-syenite (Syn.: Mangerite), etc.

Trachyte HAÜY. The term trachyte, from the Greek τραχύς, on account of the rough appearance of the rock, was introduced by Haüy[3] in his lectures at the Jardin des Plantes to characterize the rocks from the Drachenfels on the Rhine. Although the feldspar in these rocks had previously been determined and named sanidine by Nose,[4] yet plagioclase rocks of the general appearance of the original trachyte came to be included in the term. Later, von Buch[5] separated certain Andean extrusives with plagioclase from this group and called them andesites. At the present time trachyte is used for the extrusive equivalents of syenite, that is, for rocks consisting of potash-feldspar, a little plagioclase, and a biopyribole. Many trachytes are orthotrachytes (2111).

(2213) Monzonite DE LAPPARENT-BRÖGGER. The principal rock of Monzoni, in the Tyrol, is of quite variable character. It

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, II," *Tscherm. Min. Petr. Mitth.*, XIX (1900), 173.

[2] B. Polenov, "Die massigen Gesteine von nordlichen Theile des Witim-Plateau," *Travaux de la Société Impériale des Naturalistes de St. Pétersbourg*, XXVII (1899), livr. 5, 464.

[3] Haüy did not publish the name until 1822 in his *Traité de minéralogie* (2d ed.; Paris, 1822), IV, 579, but it was accredited to him as far back as 1813 in Alexandre Brongniart's "Essai d'une classification minéralogique des roches mélangées," *Jour. d. Mines*, XXXIV (1813), 43.

[4] K. W. Nose, *Orographische Briefe*, I, 26, 113.

[5] Leopold von Buch, "Ueber Erhebungscratere und Vulcane" (read in Berlin Akad., March 26, 1835), *Pogg. Ann.*, XXXVII (1836), 190.

was called Monzon-syenit by von Buch,[1] and later monzonit by De Lapparent.[2] The latter term served as a collective name for some years, but in 1881 Reyer[3] used it as a specific name for rocks of the Monzoni type, which he thought to be augite-syenite. Earlier Tschermak[4] had recognized the principal rock to be an orthoclase-plagioclase rock, but he applied the term monzonite to the whole series. Lemberg[5] characterized the rock as intermediate between syenite and diorite. In those days rocks were classified either as syenites or diorites, and it was not until 1895 that an intermediate family was established. In that year Brögger[6] introduced the monzonite family. He says: "Es ist . . . . nach meiner Ansicht nothwendig, zwischen den Orthoklasgesteinen und den Plagioklasgesteinen . . . . eine Übergangsordnung von Alkalifeldspath-Kalknatronfeldspath-Gesteinen einzuschieben." The plagioclase of the Monzoni rocks, according to Brögger, is generally andesine to labradorite, or even anorthite.[7] Rosenbusch[8] says that andesine is much rarer in all monzonites than more basic plagioclase, and more acid plagioclase than andesine had not been observed by him in the rocks of Monzoni. Elsewhere, it would seem, orthoclase-acid-plagioclase rocks are more common than those with basic plagioclase. In this classification, therefore, the more acid rocks, that is, those whose feldspar is oligoclase or andesine (sodimonzonites), will be considered normal monzonites, while those with labradorite or bytownite will be included under the calcimonzonites (2313).

[1] Leopold von Buch, "Ueber geognostische Erscheinungen im Fassathale," *v. Leonh. Mineralogisches Taschenbuch für das Jahr 1824*, p. 347.

[2] M. de Lapparent, "La constitution géologique du Tyrol, méridional," *Ann. d. Mines*, 6 sér., VI (1864), 259.

[3] Ed. Reyer, "Predazzo," *Jahrb. d. k. k. geol. Reichsanst.*, XXXI (1881), 36.

[4] Gustav Tschermak, *Die Porphyrgesteine Österreichs* (1869), p. 110.

[5] J. Lemberg, "Über die Contactbildungen bei Predazzo," *Zeitschr. d. d. geol. Gesell.*, XXIV (1872), 188, 190.

[6] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), pp. 22–23.

[7] *Op. cit.*, p. 54.

[8] H. Rosenbusch, *Elemente der Gesteinslehre* (Stuttgart, 1898), p. 108; also *Mikroskopische Physiographie der massigen Gesteine* (Stuttgart, 1907), II[1], 167.

Certain intrusive rocks in Banat, cutting through limestones and crystalline schists, were named banatites by von Cotta.[1] They are usually quartz-bearing, and are intermediate between quartz-diorites, quartz-augite-diorites, diorites, and augite-diorites. Brögger[2] applied the name to quartz-bearing monzonites, intermediate between normal monzonites and adamellites, and related to monzonites as quartz-syenites are to syenites. The extrusive equivalent of banatite BRÖGGER is quartz-trachyte-andesite BRÖGGER[3] (see note under 229).

Olivine-monzonite. While the Monzoni olivine-monzonites carry basic plagioclase, elsewhere olivine-monzonites with andesine are found. These rocks, therefore, fall in the present subfamily. Kentallenite is stated by Hatch[4] to be "identical with Brögger's olivine-monzonite. . . . . The two feldspars are present in roughly equal proportions." As a matter of fact, Hill and Kynaston[5] distinctly state that "the term (monzonite) has come to be associated with the presence of an approximately equal amount of the two feldspars—a feature which cannot be said to be an essential characteristic of our group." From the variation in the various specimens described, it would seem that kentallenite is an olivine-orthoclase-plagioclase rock, the ratio of the feldspars being quite variable, consequently not limited to Family 13 here.

Latite RANSOM. The name latite, from the occurrence of such rocks in the Italian province of Latium, was used by Ransom[6] for the extrusive equivalents of the monzonites.

Syn.: Trachyte-andesite. (The term trachy-andesite has been used in a different sense from trachyte-andesite by some writers, though others make it synonymous. Rosenbusch[7] uses

[1] B. von Cotta, *Erzlagerstätten im Banat und in Serbien* (Wien, 1864).

[2] W. C. Brögger, *op. cit.* (II, 1895), p. 61. [3] *Ibid.*, p. 60.

[4] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), pp. 206–7.

[5] J. B. Hill and H. Kynaston, "On Kentallenite and Its Relation to Other Igneous Rocks in Argyllshire," *Quart. Jour. Geol. Soc.*, LVI (London, 1900), 532.

[6] F. Leslie Ransome, "Some Lava Flows of the Western Slope of the Sierra Nevada, California," *Amer. Jour. Sci.*, V (1898), 372.

[7] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (Stuttgart, 1908), II, 1036–37.

it, by analogy to trachydolerite, for an extrusive rock whose deep-seated equivalent would be intermediate between alkali-syenite and essexite. It represents, consequently, a rock carrying a feldspathoid or aegirite, riebeckite, etc., and not, as one would suppose from the name, a rock intermediate between trachyte and andesite.)

(2214) **Monzodiorite.** The term syenodiorite was proposed by the writer[1] for the quartz-free equivalent of granodiorite. For the reasons stated under granodiorite (229), this term is withdrawn and monzodiorite is substituted for it.

Syn.: Syenite-diorite BRÖGGER.[2]

Andelatite. For the extrusive equivalent of monzodiorite, the term andelatite, as intermediate between andesite and latite, is suggested. See note under granodiorite (229).

Mugearite HARKER. Mugearite, from the village of Mugeary, is the name given by Harker[3] to certain extrusive rocks resembling basalt but with oligoclase (Ab_7An_2) and much olivine. A modal analysis shows the rock to consist of oligoclase 57½ per cent, orthoclase 12½ per cent, olivine, iron ore, and augite (augite quite subordinate to olivine) 26½ per cent, and apatite 3½ per cent. It is therefore an olivine andelatite.

(2215) Diorite HAÜY. The term diorite (from *διωρίζω*, "distinct") was introduced by Haüy[4] as a substitute for Werner's term *Grünstein*. The name now stands for a rock consisting of acid plagioclase and a dark mineral.

Syn.: Grünstein WERNER, Diabase BRONGNIART.

Oligoclase-diorite.

Andesine-diorite.

Andesite VON BUCH. Formerly there were included, under the name trachyte, not only orthoclase rocks, but those

[1] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 89.

[2] W. C. Brögger, "Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite," Part I, *Zeit. f. Kryst.*, XVI (1890), 49.

[3] Alfred Harker, "The Tertiary Igneous Rocks of Skye," *Geol. Surv. Mem.* (1904), p. 265; John S. Flett, "On the Mugearites," *Summary of Progress, Geol. Surv.* (1907), p. 119.

[4] The term first appeared in the publications of some of Haüy's students. Thus see J. F. d'Aubisson de Voisins, *Traité de géognosie* (Strasbourg and Paris, 1819), p. 146. Later it was used in Abbé Haüy's *Traité de minéralogie* (Paris, 1822), IV, 540.

containing plagioclase as well. See note under trachyte (2212). In 1835 von Buch[1] described certain volcanic rocks from the Andes, consisting of plagioclase (originally thought to be albite) and hornblende. He named them andesites. Later the term was applied to oligoclase- or andesine-bearing rocks, and it is used in this sense here. The dark mineral may be biotite, hornblende, or augite, or combinations of these, which thus give subfamilies.

Biotite-andesite.

Mica-andesite.

Hornblende-andesite.

Syn.: Hungarite LANG,[2] named from their wide distribution in Hungary.

Augite-andesite. See note under basalt (2315).

Hypersthene-andesite BECKE.[3]

Syn.: Santorinite BECKE. Becke[4] proposed the term santorinite for acid- and alboranite for basic rocks of Santorin. The former are hypersthene-andesites rich in soda (Na:Ca > 2). The phenocrysts are labradorite with mantles of oligoclase, while the groundmass is acid oligoclase. The average feldspar, therefore, is acidic. Washington[5] had previously called the acid rocks pyroxene-andesites and had proposed the term santorinite for the members carrying basic plagioclase. Santorinite, used with two meanings, should therefore be abandoned.

(2217) Nephelite- (leucite-) bearing syenite.

(2218) Nephelite- (leucite-) bearing monzonite.

(2219) Nephelite- (leucite-) bearing monzodiorite.

(2220) Nephelite- (leucite-) bearing diorite.

(2222) Nephelite-syenite ROSENBUSCH. Rosenbusch[6] included,

[1] Leopold von Buch, "Ueber Erhebungscratere und Vulcane" (read in Berlin Akad., March 26, 1835), *Pogg. Ann.*, XXXVII (1836), 190.

[2] Heinr. Otto Lang, *Grundriss der Gesteinskunde* (Leipzig, 1877), p. 196.

[3] F. Becke, "Der Hypersthen-Andesit der Insel Alboran," *Tscherm. Min. Petr. Mitth.*, XVIII (1899), 553.

[4] *Ibid.*, p. 553.

[5] Henry S. Washington, "Italian Petrological Sketches: V. Summary and Conclusions," *Jour. Geol.*, V (1897), 368.

[6] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (1st ed.; Stuttgart, 1877), II, 204.

under the names Eleolith-Syenit and Nephelin-Syenit, rocks which had previously been described as zircon-syenite, foyaite, miascite, and ditroite. If these terms were not acceptable he suggested that all of the rocks of this class be included under foyaite, since the rocks from Mount Foya, in the Serra de Monchique, province of Algarva, Portugal, as originally described by Blum,[1] are most nearly representative of the whole group. The term eleolite has fallen away, more or less, since the age element in mineralogy is no longer considered, and in general, in this country, the rocks have been called nephelite-syenites. Brögger[2] proposed to subdivide the nephelite-syenites into two groups according to texture. For rocks of this composition and with trachytoid texture he used Blum's term foyaite, and for those with granitic texture Zirkel's[3] term ditroite. In the present classification, under the term nephelite-syenite, are included those nephelite-bearing rocks in which orthoclase exceeds acid plagioclase (oligoclase or andesine) in amount. The rocks in which the plagioclase is albite are here called albite-nephelite-syenites (2122), and those which contain no plagioclase, ortho-nephelite-syenites (212).

Foyaite BLUM-BRÖGGER.

Ditroite-ZIRKEL-BRÖGGER.

Syenoid SHAND. As an abbreviation for feldspathoid-syenite, Shand[4] used syenoid, and said the term would "imply the presence of nephelite." He further suggested that gabbroid, dioroid, and doleroid might be advantageously coined in the same manner. Syenoid could well be used as a family name to include both nephelite and leucite rocks.

Leucite-syenite.

[1] R. Blum, "Foyait, ein neues Gestein aus Süd-Portugal," *Neues Jahrb.* (1861), p. 426.

[2] W. C. Brögger, *op. cit.*, *Zeitschr. f. Kryst.*, XVI (1890), pp. 39, 125; also *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits* (Kristiania, 1898), pp. 164–65.

[3] F. Zirkel, *Lehrbuch der Petrographie* (1st ed.; Bonn, 1866), I, 595. The term is derived from Ditró, in eastern Siebenbürgen, Transylvania.

[4] S. J. Shand, "On Borolanite and Its Associates in Assynt," *Trans. Edinburgh Geol. Soc.*, IX (1910), 377.

(2223) Nephelite-monzonite. Under this name Lacroix[1] described rocks from Madagascar consisting essentially of anorthoclase, basic labradorite, nephelite, titaniferous pyroxene, barkevikite, titaniferous magnetite, and apatite. The mineral proportions are quite variable. To make it conform with the usual monzonite group, the term nephelite-monzonite is here adopted for a nephelite rock of Class 2 with *acid* plagioclase about equal in amount to the other feldspars. The rock described by Lacroix is included under the calci-nephelite-monzonite family.

Nephelite (**leucite-**)latite. The extrusive equivalent of the preceding.

(2224) **Nephelite-(leucite-)monzodiorite.** A term here suggested for nephelite-(leucite-)bearing rocks comparable to granodiorites among the quartz-bearing.

(2225) **Nephelite-(leucite-)diorite.** A term, analogous to nephelite-syenite, here suggested for nephelite-acid plagioclase rocks. Under this family would fall Adams and Barlow's[2] raglanite, an abnormal rock on account of its large content of corundum, 4.45 per cent. Since it carries only 12 per cent by weight of nephelite, it is also far from the center point.

Nephelite-(leucite-)tephrites and nephelite-(leucite-) basanites belong here in part.

(2229) No plutonic rock has been located in this family, but there is an extrusive, a leucite-tephrite from the Roman Comagmatic region, described by Washington.[3]

(2230) A leucitite from the Roman Comagmatic region, described by Washington,[4] is the only rock yet found here.

[*To be concluded*]

[1] A. Lacroix, "Sur les granites et syénites quartzifères à aegirine, arfvedsonite et aenigmatite de Madagascar," *Comptes Rendus*, CXXX (1900), 1208; also "Sur la province pétrographique de Nord-ouest de Madagascar," *ibid.*, CXXXII (1901), 439.

[2] Frank D. Adams and Alfred E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Mem. Geol. Surv. Canada*, No. 6 (1910), p. 314.

[3] Henry S. Washington, "The Roman Comagmatic Region," *Carnegie Publication. No.* 57 (Washington, 1906), p. 73.

[4] *Ibid.*, p. 136.

Reviews

The Environment of Vertebrate Life in the Late Paleozoic of North America; A Paleogeographic Study. By E. C. Case. Carnegie Institution: Washington Publication No. 283, 1919. Pp. 273, figs. 8 and two correlation tables.

This publication will be welcomed by all geologists as a signal contribution to the interpretation of conditions of the late Paleozoic. Dr. Case is well qualified to summarize the conditions surrounding the vertebrates, and to draw conclusions as to the influence of the environment on their development and distribution.

In the first chapter the various methods of attack and the complexity of the factors in any paleogeographic problem are briefly presented. There follows a summary of late Paleozoic rocks in the several provinces of North America. For the most part the descriptions are quotations from other writers and are not intended to present new material. Quite apart from the obvious purpose, this summary will be of great use to the student, gathered as it is from a voluminous literature on the subject. The selections are well made; they are representative of current opinion, to the point, and show no evidence of an attempt on the part of the compiler to prove a point. The full usefulness is slightly impaired, perhaps, by the absence of an index. The accompanying correlation tables differ little from generally accepted views.

Contrary to what might be expected, the author makes no attempt to fix the lower boundary of the Permian. Throughout the work he refers repeatedly to Permo-Carboniferous times in the sense of a transition period between the Pennsylvanian and the closing events of the Paleozoic. He makes a sharp distinction, however, between Permo-Carboniferous *times* and Permo-Carboniferous *conditions*, and emphatically states that these two things are not necessarily coincident. Perhaps the most important deduction reached, together with the dependent conclusions, is that Permo-Carboniferous conditions prevailed in the east, starting with Mid-Conemaugh time, and reached the southwest considerably later. The deposition of red sediments is taken to mark the introduction of important new climatic and physiographic conditions and accompanying changes—Permo-Carboniferous condi-

tions. These conditions spread very slowly from east to west and, therefore, have left a record oblique to stratigraphic lines (see Fig. 1).

The environment of an organism, "the sum total of all its contacts with the external world," determines to a great extent its structural changes and the distribution of its kind. The equable, humid climate and topographic uniformity of the typical (lower) Pennsylvanian produced an abundant though fixed food supply—vegetation. Since new forms arise only through isolation (not necessarily geographic isolation) the monotony of this environment acted as a repressive force, checking the expansion of the amphibians and reptiles into new forms. "Environmental monotony would result in the persistence of older and simpler types, because the variants, possibly being constantly produced, would not have a chance to develop."

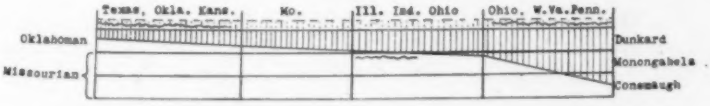


FIG. 1.—"Diagram illustrating in a schematic way the relative position of the sediments formed under Permo-Carboniferous conditions. The land was rising from east to west, but there was continuous sedimentation in the eastern region at the western edge of the rising land of Appalachia. As the land rose slowly the red beds spread toward the west, occupying relatively higher positions in the stratigraphic column. It is difficult to illustrate the actual conditions in the diagram, because the 'red beds conditions' were advancing, but the wavy lines indicate the surface of the ground relative to these conditions. In Pennsylvania and West Virginia deposition was continuous during the conditions. In Illinois and Indiana deposition had ceased by the time the conditions reached that far west; in Kansas, Oklahoma, and Texas 'red-bed conditions' reached the region in time to affect only the uppermost Paleozoic deposits. The upper limit of the red-bed conditions is not known, and so the upper limit of the wedge is indicated by a dotted line" (from Case, p. 192).

Permo-Carboniferous conditions included a cool to cold, arid or semiarid climate, resulting from deformation throughout various parts of the world, the presence of volcanic dust in the air, and a diminution of the carbon-dioxide content of the atmosphere. This made for a great variety in environmental conditions and destroyed the repressive bounds to vertebrate expansion. "The fauna, long restrained from any expression of evolutionary tendencies, full fed, and in the vigor of its youth, responded at once to the change, and new forms appeared so suddenly as to be unheralded in the preserved remains."

These new forms appeared at higher and higher horizons as the Permo-Carboniferous conditions spread slowly westward and "to correlate widely separated groups of beds as synchronous in deposition because of a similarity, even approaching identity, in the fauna or flora would be a serious error."

M. G. M.

Upper Cretaceous Floras of the Eastern Gulf Region in Tennessee. Mississippi, Alabama, and Georgia. By E. W. BERRY. U.S. Geological Survey, Professional Paper 112, 1919. Pp. 177, pls. 33, figs. 12.

Another publication is added to the already considerable list which is making fossil plants such an important part of our geological knowledge of the southeastern United States.

The Upper Cretaceous of the eastern Gulf region extends in a lunate outcrop around the southern end of the Appalachians. It is subdivided into the Tuscaloosa formation, the Eutaw formation, the Selma chalk, and the Ripley formation. These formations, with the exception of the Selma, are made up largely of cross-bedded sands, with associated clays.

The most extensive flora is that of the basal Tuscaloosa formation, comprising 151 species of which the majority are dicotyledonous angiosperms. The place of origin of this dominant element is left unsettled, but the idea of their dispersal from an Arctic area is consistent with the evidence offered by this and other Cretaceous floras. This flora is made up largely of lowland coastal types, and its ecological character is in accord with other evidence of the delta origin of the formation. The plants make up an assemblage which most nearly resembles the modern warm-temperate rain forest. In view of their northward range into Greenland, they may be said to indicate a climate mild over wide areas.

The Eutaw flora comprises 43 species, most of which come from the basal portion of the formation and closely resemble those from the Tuscaloosa formation. The physical conditions suggested by this flora are similar to those for the Tuscaloosa.

The Selma chalk, which is described as a lithologic rather than a chronologic unit, is entirely marine and contains no plant remains. The Ripley formation contains a few poorly preserved plant fossils.

The Tuscaloosa formation may be correlated, on the basis of its contained flora, with the upper part of the Raritan and with the Magothy

formations to the north, with the Woodbine sand of southern Texas, and with the Dakota sandstone of the western interior. The Eutaw flora closely resembles the floras of the Black Creek and Magothy formations of the Atlantic Coastal Plain. It cannot be closely related to any of the western floras, but since it is decidedly older than the Montana flora the Eutaw formation may be considered to be synchronous with part of the Dakota and with the Colorado series. The flora of the lower part of the Ripley is related closely to those of the Black Creek, Magothy, Tuscaloosa, and Raritan formations,while that of the upper part shows little relation to any of the earlier Cretaceous floras.

R. W. C.

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